ARIZONA DEPARTMENT OF TRANSPORTATION

REPORT NUMBER: FHWA-AZ87-808

CALIBRATION OF MARSHALL HAMMER

State of the Art

Final Report

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June 1987

Prepared for:
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in cooperation with
U.S. Department of Transportation
Federal Highway Administration

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
FHWA-AZ87-808		

4. TITLE AND SUBTITLE	5. REPORT DATE
CALIBRATION OF MARSHALL HAMMER	June 1987
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Zahur Siddiqui, Martin W. Trethewey, and David A. Anderson	8. PERFORMING ORGANIZATION REPORT NO. PTI 8710
9. PERFORMING ORGANIZATION NAME AND ADDRESS Pennsylvania Transportation Institute Pennsylvania State University Research Building B University Park, PA 16802	10. WORK UNIT NO.
	11. CONTRACT OR GRANT NO. HPR-PL-1(31)ITEM 808
12. SPONSORING AGENCY NAME AND ADDRESS ARIZONA DEPARTMENT OF TRANSPORTATION 206 S. 17TH AVENUE PHOENIX, ARIZONA 85007	13. TYPE OF REPORT & PERIOD COVERED Final Report January 1987 - June 1987
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. ABSTRACT

The Marshall method of mix design is one of the most widely used methods for the design and control of hot-mix paving mixtures in the country. However, discrepancies between test results occur when different Marshall equipment is used, often leading to dispute when verification or acceptance of test results significantly vary from the contractor's quality control results.

This research identified key equipment-related factors associated with discrepancies in test results obtained by different compaction and testing. Operator-related factors and subtle differences in the interpretation of the standard procedure add to the complexity of the system. Techniques and procedures for quantifying the effects of these variables and their interactions are currently unavailable. While the need for a calibration procedure for the Marshall compaction equipment is apparent, in the absence of such a procedure, several U.S. and Canadian private and public agencies regularly participate in round-robin or mix exchange programs, which are discussed. To examine the ability to measure the fundamental process parameters of the Marshall hammer operation, several mix specimens were compacted with a mechanical hammer instrumented with accelerometers. From the analysis of data obtained, it was concluded that technology for measuring the amount of energy delivered to the specimen during the compaction process is currently available. Research and development needed for adapting this technology to the field calibration of the Marshall hammer is recommended.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Asphalt concrete, mix design, Marshall method, mix control compaction density, stability, flow	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	74	

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INTRODUCTION

The Marshall method of mix design and control was originally developed in the late 1930s by Bruce G. Marshall of the Mississippi Highway Department. The method evolved during the period from World War II to the late 1950s when the Department of Defense felt a need for a procedure that could be used for designing asphalt concrete mixes to withstand increasing wheel load and tire pressures of Military Aircraft [1]. Today the Marshall method of mix design is one of the most widely used methods for the design and control of hot-mix paving mixtures [2]. However, the current method has evolved through a number of changes and refinements [1].

In its current form, the Marshall method of mix design consists essentially of (1) compacting specimens of the mix, (2) conducting a density-voids analysis on the compacted specimens, and (3) testing the compacted specimens for stability and flow. Details of the procedure and equipment are provided in the ASTM (D 1559), AASHTO (T 245), and Military (MIL-STD-620A) standards, given in Appendix A. The ASTM standard (D 1559) specifies the use of a manual compaction hammer, while both AASHTO and MIL-STD-620A permit the use of a mechanical hammer, provided it is properly correlated with the standard hand hammer. Currently, however, most highway agencies and contractors use a mechanical hammer for the purpose of design, control, and acceptance of hot-mix asphalt concrete. During construction, periodic process control tests are performed by the contractor, while acceptance testing usually is conducted by the agency.

Industry and highway agency personnel have long been aware of discrepancies between test results when mix specimens are prepared and tested in different Marshall equipment [3,4]. This situation can often lead to dispute when verification/acceptance test results significantly vary from the contractor's process control results. The objectives of this research were (1) to identify the key equipment-related factors associated with discrepancies in test results obtained by using different equipment, and (2) to recommend calibration equipment and techniques that could be adopted by the Department to confirm the acceptability of different Marshall equipment.

TASK 1. IDENTIFICATION OF VARIABLES

Personal experience of the research team, review of available literature, and preliminary discussions with knowledgeable agency/industry personnel indicated that several types of hot-mix compaction equipment are currently used in the laboratory, i.e., manual (unsupported) hammer, manual (supported) hammer, and mechanical hammer. The Marshall method was originally developed for a hand-held, unsupported hammer. However, some agencies use a tripod in order to keep the rod of the manual hammer vertically aligned. This hammer is referred to as a manual, supported hammer. Even within a particular type of compactor there may be differences that could affect the results obtained. For example, some mechanical compaction devices incorporate a system whereby the mold rotates during the compaction process. Other hammers have a bevelled foot rather than a flat foot.

The research team prepared a preliminary list of 12 compaction-equipment-related variables that may have an influence upon the level of compaction achieved in the laboratory (Table 1). From this list, eight key variables were selected and included in a questionnaire (Appendix B) used for conducting telephone interviews with several agency and industry personnel and researchers at universities. The people contacted have many years of experience in the bituminous concrete area and continue to be active in this field.

A total of 11 persons was interviewed. Two of these were university-based researchers with national reputations; two were from large, private material testing laboratories; one represented a large paving contractor; one, a consultant currently conducting research on a federally-sponsored project related to bituminous concrete; and five were from progressive state highway agencies (including one from Canada). Three of these state highway agencies, and several other people contacted, have also been involved in a series of round-robin (mix exchange) testing programs with the objective of studying the variability in Marshall test results. Some of these round-robin testing programs are discussed later in this report.

Table 1. Compaction-equipment-related variables that may influence test results.

1. Type of hammer
   - manual (unsupported)
   - manual (supported)
   - mechanical
   - gyratory
2. Hammer foot
   - flat vs. bevelled
3. Compaction mold (restraint)
   - rotating vs. fixed
4. Surcharge on hammer assembly
   - spring vs. dead weight
5. Weight of hammer
6. Height of free fall
7. Friction between rod and sliding weight
8. Hammer alignment
9. Compaction pedestal (base type)
   - standard vs. nonstandard,
   - wood block vs. no pedestal
10. Base support (equipment location)
    - ground floor
    - first floor
    - second floor
11. Contact between mold base plate and top of equipment assembly base
12. Dynamic response from energy transfer (during impact)

The frequency with which the persons surveyed rated individual variables (see question 5 of Appendix B) as important to the level of compaction achieved in the laboratory is summarized in Table 2. Except for "mold restraint" and "dynamic response from energy transfer during impact," all variables were considered to have a significant influence upon the level of compaction achieved.

Ten of 11 persons interviewed had experienced discrepancies between test results when hot-mix asphalt concrete samples were compacted in different Marshall equipment. Among the 11 surveyed, Marshall compaction hammers manufactured by Rainhart were the most commonly used equipment. Some agencies fabricate their own compaction equipment. The age of the Marshall hammers used by the people surveyed ranged between 7 and 20 years. However, the equipment is periodically inspected and parts are replaced/repaired as needed.

Based on answers to question 3 of the questionnaire, significant differences are perceived in Marshall compaction equipment made by different manufacturers. One of the differences cited pertains to the mass of the sliding weight, and the experience of the research team confirms this discrepancy among equipment. Two Marshall hammers from different manufacturers were ordered for the laboratory of the Pennsylvania Transportation Institute. When the hammers were received, it was found that the sliding weights differed by 266 g. Among the major differences observed between compaction equipment were the type of reaction (base support) and the shape of the hammer assembly foot (flat versus bevelled).

Eight of the 11 persons interviewed attributed differences in compaction test results to both equipment- and operator-related factors. When asphalt concrete mix specimens are compacted in a given compactor, differences in the compaction temperature and the actual preparation of the samples can significantly influence the test results. Clearly, these are operator-related variables. In addition, a laboratory technician who has been preparing and testing Marshall specimens for several years may, for the purpose of convenience, develop some "short-cuts" to the procedure without realizing that he is deviating from the specified procedure.

Table 2. Frequency with which variable was considered important to compaction achieved.

Compaction-equipment-related variable	Number of persons rating variable as important to compaction achieved
1. Weight of hammer	7
2. Height of free fall	8
3. Friction between rod and hammer	6
4. Base type	7
5. Mold restraint (rotating vs. fixed)	3
6. Alignment of hammer	9
7. Dynamic response from energy transfer during impact	3
8. Base support (foundation)	9

In addition to compaction density (and the associated air voids), asphalt concrete mixes are also tested for stability and flow. Stability is a measure of the relative strength of two different mixes; flow measures the plasticity of a mix.

The Marshall stability and flow of compacted mix specimens are determined with the help of a "breaking head" and "flowmeter" (Appendix A). Nine of the 11 persons interviewed had experienced discrepancies in these devices. The major discrepancy was associated with the dimensions of the breaking head, including the dimensions of the bevel. While test standards require a 1/4-inch bevel, breaking heads with 3/8-inch bevels have been encountered. Often the breaking head does not have the standard 2-inch radius. Research has shown that these differences in the breaking head result in discrepancies in the stability and flow measurements [3]. Again, operator-related factors, such as conditioning of the specimen and the testing head, duration of the actual testing process, etc., can add to the differences between test results.

Another factor affecting the congruity of test results in the mount of the compaction pedestal. All persons contacted have their Marshall hammers mounted on the standard compaction pedestal fixed to the concrete of the ground floor of the building. However, several of the interviewees have encountered situations where the standard compaction pedestal was not used or the equipment was located on an upper floor of the building. The experience of the research team and the persons surveyed indicates that such nonstandard reaction can significantly affect Marshall test results.

Marshall Round-Robin and Mix-Exchange Programs

Discrepancies in Marshall test results have long been of concern to both industry and state highway agency personnel. ASTM Subcommittee D04.20, private testing laboratories such as the AASHTO Materials Reference Laboratory (AMRL) and the Chicago Testing Laboratory, and several state highway agencies, both in the United Sttes and in Canada, have conducted extensive interlaboratory testing programs to study the repeatability and reproducibility of Marshall test results. The research team is familiar with the study conducted by the ASTM Subcommittee D04.20 and has reviewed the study results. However, at the present time, the results of that ASTM study have not been published and, at the request of the ASTM Subcommittee, cannot be discussed in this report. The states of Georgia and Utah have conducted in-house research to study the variability in Marshall test results. While these studies have not been published, the researchers have obtained special permission to summarize the studies in this report.

In 1980, Georgia conducted an interlaboratory investigation in which five laboratories participated. The central laboratory weighed and separately packaged the aggregate for each sample before shipping it to the participating laboratories. Each laboratory prepared and tested the mixes in accordance with the recommended procedure. Each laboratory used both a manual and a mechanical hammer. The graphs shown in Figure 1 represent results for the Marshall properties tested: VMA, voids, voids filled, stability, flow, and the relationship between the mechanical and hand hammer. On each graph, "H" and "M" represent the hand hammer and the mechanical hammer, respectively. In each laboratory, the mechanical hammer yielded higher VMA, higher voids, lower voids filled, lower stability, and lower flow than the hand hammer. The higher specimen densities obtained with the manual hammer may be attributed to the kneading action which takes place when the hammer strikes the sample at a slight angle from the vertical [2]. These results are in general agreement with the experiences of the persons contacted during telephone interviews.

In 1986, four laboratories of the Georgia state highway department and five industry laboratories cooperated in a study for comparing test results associated with the standard 50-blow Marshall procedure. Georgia's asphaltic concrete B mix was used. The research results are shown in Table 3. Georgia's criteria require a review of the procedure and/or equipment if a laboratory average exceeds the following ranges when compared to the overall average:

Density $\pm$ 1.5 lb/ft^3
Stability $\pm$ 400 lb
Flow $\pm$ 0.02 in.

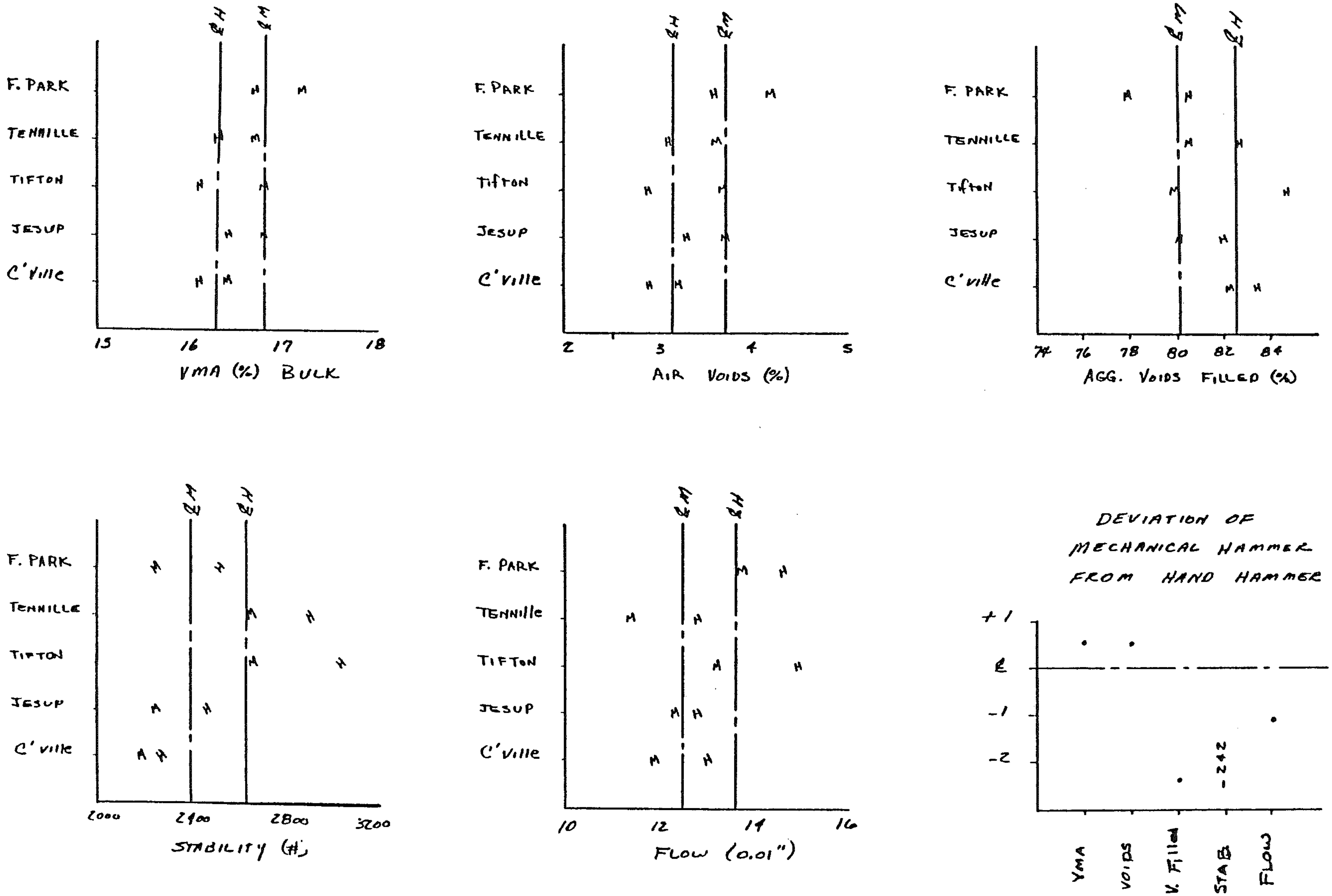


Figure 1. Marshall co-op test results (courtesy of Mr. Ron Collins, Georgia DOT).

Table 3. Asphalt concrete comparison testing.*

Lab	Location	Height	Density (PCF)	% Voids	Stability	Flow
District 2	Tennille, Ga.	2.55	154.4	4.3	2500	12
		2.60	150.3	6.8	2240	12
		2.51	155.6	3.6	3020	15
District 4	Tifton, Ga.	2.50	154.8	4.1	2880	13.1
		2.50	152.9	5.3	2350	13.3
District 5	Jesup, Ga.	2.50	154.6	4.2	2200	15.0
		2.50	154.3	4.4	2175	14.8
		2.50	154.6	4.2	2275	13.6
District 7	Forest Park, Ga.	2.562	153.0	5.2	2100	12
		2.555	154.1	4.5	2460	13
		2.540	154.3	4.4	2520	11
Southern Aggregate	Macon, Ga.	2.567	153.1	5.1	2150	10
		2.574	153.6	4.8	2190	9
		2.562	153.6	4.8	2340	10
APAC-Georgia	Atlanta, Ga.	2.56	152.6	5.4	2320	11
		2.56	153.2	5.1	2470	13
		2.56	152.8	5.3	2330	13
Metro Materials	Doraville, Ga.	2.44	154.4	4.3	2200	9
		2.50	153.6	4.8	2050	10
		2.50	152.5	5.5	1950	10
Vulcan Materials	Birmingham, Ala.	2.51	153.0	4.9	2400	13.5
		2.50	157.0	2.9	2650	13.5
		2.50	155.0	3.8	2250	12.0
Vulcan Materials	Chattanooga, Tenn.	2.615	152.9	5.3	2550	11
		2.615	151.6	6.0	2550	10
		2.615	150.8	6.5	2525	12
Average (from all labs)			153.6	4.8	2371	12.0

*Data courtesy of Mr. Ron Collins, Georgia DOT

In light of these criteria, the stability measurements shown in Table 3 are fairly consistent. But, density and flow values have a greater range. For example, only the District 7 laboratory met the tolerance for flow. In addition, several participating laboratories failed to meet the requirement that compacted specimens have a thickness of 2.50 ± 0.05 inches. The results obtained from the Georgia studies tend to support the experience of the researchers that discrepancies in Marshall test results are due to both equipment- and technician-related factors.

In 1979, a Marshall equipment correlation study was conducted by the Utah DOT. The objective of the investigation was to study the effect resulting from the technician and equipment (Marshall hammer and breaking head). Mix specimens were prepared, compacted, and tested at three levels of asphalt-content: 5.5, 6.0, and 6.5 percent.

Table 4 summarizes test results where the entire process of preparing, compacting, and testing samples was conducted by one technician from the central laboratory. The technician prepared the aggregate samples at the central laboratory and performed the balance of the process at each district laboratory using the same Marshall hammer and breaking head. Table 5 represents data where the same technician prepared the aggregate samples at the central laboratory. However, these samples were then shipped to the district laboratories, where a district technician prepared, compacted, and tested the mix specimens using the district's Marshall hammer and breaking head. A comparison of the two sets of results indicates that, except for flow, the averages of property values were fairly consistent. However, it is evident from a comparison of the values for range and standard deviation (Tables 4 and 5) that the operator and equipment have a significant effect on the Marshall test results. For example, the standard deviation for bulk density in Table 5 was 150 to 260 percent larger than that obtained when the same mix was prepared and tested by one operator using one set of equipment (Table 4).

Characteristics of the equipment used, procedures employed, and the results obtained during the study were reviewed by personnel at the central laboratory, and the following discrepancies were highlighted:

Table 4. Marshall equipment correlation study.*

DISTRICT	BULK DENSITY			VOIDS			VMA % FILLED			STABILITY			FLOW		
LAB	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5
1	2.29	2.29	2.30	3.3	2.4	1.5	78.7	84.7	90.6	2256	2064	1871	10	11	14
2	2.30	2.30	2.30	2.8	2.0	1.5	81.4	87.0	90.6	2477	2559	2216	9	9	12
3	2.29	2.30	2.30	3.3	2.0	1.5	78.7	87.0	90.8	2538	2642	2380	8	9	11
4	2.29	2.30	2.29	3.3	2.0	1.9	78.7	87.0	88.4	2663	2678	1825	10	11	14
5	2.30	2.31	2.30	2.8	1.6	1.5	81.9	89.4	90.6	2729	2620	2045	10	11	14
6	2.29	2.29	2.30	3.3	2.4	1.5	78.7	84.8	90.6	2367	2178	2023	8	11	12
MAIN LAB	2.29	2.29	2.29	3.3	2.4	1.9	78.7	84.7	88.4	2767	1945	1826	9	11	12
AVERAGE	2.29	2.30	2.30	3.2	2.1	1.6	79.5	86.4	90.0	2542	2384	2027	9	10	13
STANDARD DEVIATION	± .005	±.008	±.005	±.024	±.30	±.19	± 1.4	± 1.7	±1.1	±190.1	±310	±211	± .9	± 1.0	±1.3
RANGE	1	2	1	0.5	0.8	0.4	3.2	4.7	2.4	511	733	554	2	2	3

*Data courtesy of Mr. Wade Betenson, Utah DOT.

Table 5. Marshall equipment correlation study.*

District Laboratory	Bulk Density			Measured Max. Density (Rice)			Voids			V.M.A. % Filled			Stability			Flow		
	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5	5.5	6.0	6.5
1	2.28	2.29	2.29	2.36	2.34	2.33	3.3	2.1	1.5	78.3	86.2	90.6	2776	2691	2237	10	10	12
2	2.31	2.31	2.31	2.36	2.35	2.33	2.2	1.5	0.9	84.9	90.0	94.2	3528	3194	2494	16	17	19
3	2.28	2.28	2.28	2.36	2.34	2.33	3.5	2.7	1.9	77.6	83.0	88.2	3012	3000	2664	10	11	13
4	2.29	2.30	2.29	2.37	2.35	2.33	3.3	2.0	1.9	78.8	87.0	88.5	2450	2762	2109	7	10	12
5	2.29	2.30	2.30	2.37	2.35	2.34	3.4	2.1	1.7	78.6	86.6	89.5	2790	2455	2065	10	10	13
6	2.29	2.30	2.29	2.37	2.35	2.33	3.4	2.1	1.7	78.4	86.3	89.4	3561	3224	2572	7	8	11
Main Lab	2.28	2.30	2.30	2.36	2.34	2.33	3.6	2.0	1.4	77.2	87.0	91.4	2166	2158	1921	14	14	17
Average	2.29	2.30	2.30	2.36	2.346	2.33	3.2	2.1	1.6	79.1	86.6	90.2	2897	2783	2295	11	11	14
Standard Deviation	±.013	±.012	±.009	±.005	±.005	±.007	±0.47	±0.36	±0.35	±2.0	±2.0	±2.1	±518	±391	±284	±3.49	±2.91	±2.95
Range	0.03	0.03	0.03	0.01	0.01	0.01	1.4	1.20	0.9	7.7	7.0	6.0	1395	1036	734	9	9	8

*Data courtesy of Mr. Wade Betenson, Utah DOT.

1. The size (weight) of the individual batches of aggregate and bitumen and, therefore, the height of the compacted specimens, was not consistent. The standards require that the appropriately compacted specimen should have a height of 2.5 $\pm$ 0.05 inches.

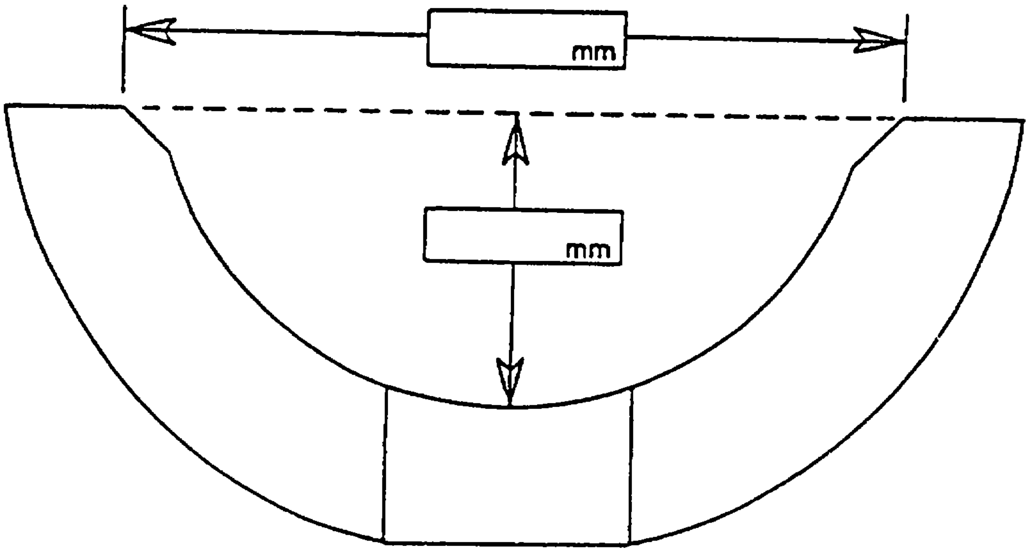
2. Several district laboratories used hydraulic jacks (instead of the testing machine) to extract the compacted specimens from the mold.

3. District laboratories were using nonstandard breaking heads.

Nonstandard breaking heads were also encountered in a recent Canadian study which is discussed here. ASTM requirements for two key dimensions of the breaking head are schematically shown in Figure 2. In a 1983 Canadian asphalt concrete mix exchange study in which 31 laboratories participated, the horizontal dimension (H) of the breaking head was found to range between 108 mm and 126.8 mm, and the vertical dimension (V) ranged between 37.5 mm and 63 mm [3]. The value of the ratio (R = H/V) varied from 1.78 to 3.11. Based on a review of the Marshall property test results, the authors of the Canadian study concluded that part of the variation in the test results was due to the variation in the dimensions of the breaking head.

Both manual and mechanical hammers were used in the Canadian study. Results obtained with the manual hammer were fairly consistent, while large variations were associated with the mechanical hammer. The authors attributed these variations to several equipment-related factors, such as the mass, drop (free-fall), and shape of the hammer [3].

Canada has on-going mix exchange and asphalt exchange programs in which private and public laboratories from different parts of the country cooperate in the testing of bituminous mixes and asphaltic products. Each year, a different agency agrees to be the host and supplies the ingredients (aggregate and bitumen) to the participating laboratories. The laboratories agree to follow a common format or procedure (provided by the host agency) with the objective of eliminating discrepancies in various laboratory procedures and equipment and to ensure that valid comparisons of data can be made. These



Ratio : Horizontal/Vertical

ASTM Requirements :
Horizontal - 111.10 mm
Vertical - 41.30 mm
Ratio - 2.69

Figure 2. Marshall breaking head measurements.

exchange programs are considered to be extremely valuable as they allow the participating agencies to evaluate how they relate (on any given test) to other agencies or to the average of the participants.

One of the mix exchange studies was performed in 1979 [4]. The instructions issued by the host for the year (Manitoba Department of Highways and Transportation) recommended that each face of the sample should be compacted with 75 blows of the manual hammer. Also, it was required that a description of the compaction pedestal (the base supporting the mold) be submitted with the test results. These instructions were issued in light of the fact that differences in hammers and compaction pedestals had contributed to the variation in results obtained from previous mix exchange studies [3]. Another reason for providing specific instructions to the participants was to eliminate the subtle differences in the manner in which different operators/technicians interpret Standard Test Procedures [2].

TASK 2. TECHNOLOGIES FOR QUANTIFYING VARIABLES

In the previous section, key variables related to the compaction equipment were identified (Table 2). For a given asphalt concrete mix, these factors have a direct influence upon the level of compaction achieved in the laboratory. However, compaction results also affect the stability of the compacted specimens. This variability in stability results can be further compounded through the use of nonstandard or defective breaking heads, which can also affect flow values. Finally, operator-related factors and subtle differences in the interpretation of the standard procedure add to the complexity of the system [2,3].

The review of relevant literature, both published and unpublished, and interviews with knowledgeable industry and state highway agency personnel indicate that techniques and procedures for quantifying the effects of these variables and their interactions are currently unavailable. From the literature review and contact with other researchers, the need for a calibration procedure for the Marshall compaction apparatus is readily apparent. It is primarily due to the absence of such a procedure that several private and public agencies, both in the U.S. and in Canada, regularly participate in round-robin or mix exchange programs. These mix exchange programs enable laboratories to evaluate their results with reference to results obtained by the other participating laboratories. In the Canadian mix exchange program, results submitted by participating laboratories are evaluated in the following manner: The mean, standard deviation, and ± 2 standard deviation limits are calculated for all data received for each test. Any test results falling outside these limits (i.e., the 95% range) are eliminated, and a new mean, standard deviation, and ± 2 standard deviation are determined. The remaining data are checked against these new limits. This procedure is repeated until all data fall within the associated 95% range [4]. Since all participating laboratories are processing and testing the same mix, comparison of results helps each laboratory to assess how well it is performing with reference to other laboratories in the cooperative program. The procedure is illustrated in Table 6 [3].

Because of the economy of time and effort, most public and private agencies use mechanical hammers in their laboratories. AASHTO T-245 permits the use of a mechanical hammer if it is calibrated to give results comparable with the manual hammer. A procedure that has been used for calibrating a mechanical hammer is described as follows. Several samples of a given mix are compacted with a desired compactive effort (e.g., 50- or 75-blow) and a standard, nonsupported manual hammer. The average bulk density achieved is considered the target standard bulk density. Specimens of the same mix are then prepared with the mechanical hammer using a range of compactive efforts. The relationship between the bulk density and the associated compactive effort is plotted as shown in Figure 3. The number of blows that are required with the mechanical hammer to attain the target bulk density is then determined from the plot.

Calibration (i.e., number of blows) is specific to a given hammer and a given mix, however; and if more than one mechanical hammer is used in a laboratory, each one should be separately calibrated for each specified compactive effort (i.e., 50 blows or 75 blows) and for each mix tested. Data on the characteristics of mechanical hammers, listed in Table 7, were collected during a Canadian mix exchange study [4]. Table 7 shows the variations in the mass and drop of the hammer and the thickness and type

Table 6. 1983 Canadian asphalt mix exchange [2].

BRIQUETTE DATA

LAB NO.	HAND BULK	MECH. BULK	R.T.S. BULK	HAND STAB.	MECH. STAB.	R.T.S. STAB.	HAND FLOW	MECH. FLOW	R.T.S. FLOW	HAND TIME-s	MECH. TIME-s	R.T.S. TIME-s
1	2.374	2.363	2.375	11.9	11.6	12.9	12	11	12	1889	1866	1960
2	2.372	2.357	2.385	11.4	11.6	15.0	12	13	11	1810	1810	1883
3	2.389	2.384	2.396	11.5	10.8	14.2	11	10	9	2110	2162	1841
4	2.386	2.376	2.381	11.2	11.8	13.0	12	13	10	2760	2490	1860
5	2.370	2.365	2.370	8.6	8.4	9.4	10	10	9	2119	2098	1851
6	2.382	2.299	2.395	10.3	6.0	13.9	13	10	9	2400	2400	1885
7	2.394	2.382	2.398	11.7	11.2	13.8	13	11	11	1800	1800	1960
8	2.359	2.347	2.354	9.6	8.1	9.7	12	11	8	1841	1836	1923
9	2.363	2.347	2.347	9.7	7.7	9.2	8	9	10	2400	2160	1867
10	2.412	2.405	2.395	11.4	12.6	12.5	18	16	9	1860	1860	1947
11	2.390	2.317	2.399	14.0	8.2	13.3	13	13	8	1800	1800	1897
12	2.362	2.358	2.378	14.5	13.3	12.5	14	13	12	1843	1987	1875
13	-	-	-	-	-	-	-	-	-	-	-	-
14	2.397	2.335	2.384	12.5	7.6	13.4	11	12	10	2025	2025	1872
15	2.382	2.370	2.362	11.0	10.3	10.9	13	13	9	1800	1800	1840
16	2.401	-	2.393	12.1	-	14.4	*19	-	10	1885	-	1817
17	2.391	2.396	2.377	11.3	10.2	15.1	7	8	9	1800	1800	1840
18	2.393	2.380	2.378	13.8	12.7	12.0	16	13	12	-	-	1848
19	2.393	-	2.394	11.2	-	13.6	11	-	11	1800	-	1866
20	2.384	2.342	2.354	11.5	9.6	11.6	13	11	9	1850	2027	1920
21	2.377	2.330	2.399	12.9	12.1	14.4	14	12	12	1890	2040	1879
22	2.372	2.356	2.346	10.2	9.6	10.7	13	12	11	1800	1800	1930
23	2.390	2.394	2.372	12.9	14.6	11.8	12	12	9	1800	1800	1936
24	-	-	-	-	-	-	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-
26	2.383	2.369	2.386	10.5	10.1	13.8	11	10	10	2400	2400	1857
27	2.383	2.337	2.367	11.0	9.8	11.2	14	11	9	1980	2160	1897
28	*2.322	*2.273	*2.321	*5.7	*4.3	*8.2	11	11	10	1800	1800	1838
29	2.394	-	2.376	11.3	-	10.7	13	-	10	1873	-	-
30	2.401	2.385	2.397	11.8	13.4	14.1	15	16	11	1915	2082	2633
31	2.377	2.361	2.370	9.4	8.1	11.6	9	9	10	1920	2280	1826
32	-	-	-	-	-	-	-	-	-	-	-	-

ALL DATA

	HAND BULK	MECH. BULK	R.T.S. BULK	HAND STAB.	MECH. STAB.	R.T.S. STAB.	HAND FLOW	MECH. FLOW	R.T.S. FLOW	HAND TIME-s	MECH. TIME-s	R.T.S. TIME-s
n	28	25	28	28	25	28	28	25	28	1800-2400	1800-2400	1800-2400
MEAN	2.382	2.357	2.377	11.3	10.2	12.4	12	12	10			
ST.DEV.	0.017	0.031	0.019	1.8	2.5	1.9	3	2	1			
95% RANGE	2.348 - 2.416	2.295 - 2.419	2.339 - 2.415	7.7-14.9	5.2-15.2	8.6-16.2	6-18	8-16	8-12			
DATA RANGE	2.322 - 2.412	2.273 - 2.405	2.321 - 2.399	5.7-14.5	4.3-14.6	8.2-15.1	7-19	8-16	8-12			

SELECT DATA (* DATA REJECTED)

	HAND BULK	MECH. BULK	R.T.S. BULK	HAND STAB.	MECH. STAB.	R.T.S. STAB.	HAND FLOW	MECH. FLOW	R.T.S. FLOW
n	27	24	27	27	24	27	27		
MEAN	2.384	2.361	2.379	11.5	10.4	12.5	12		
ST.DEV.	0.013	0.026	0.016	1.4	2.2	1.7	2	SAME AS ABOVE	SAME AS ABOVE
95% RANGE	2.358 - 2.410	2.309 - 2.413	2.347 - 2.411	8.7-14.3	6.0-14.8	9.1-15.9	8-16		
DATA RANGE	2.359 - 2.412	2.299 - 2.405	2.346 - 2.399	8.6-14.5	6.0-14.6	9.2-15.1	7-18		

(bevelled or flat) of the compaction foot. It is possible that the associated pedestal and foundation reactions would also vary. Thus, in order to reduce the between-laboratory variation in bulk density results for a given mix, it would be necessary to calibrate each hammer used with the same standard, unsupported manual hammer. Also, the calibration procedure should be periodically repeated to account for wear and repair/replacement of equipment components. Finally, calibration of the hammer can only address the variation in bulk density. It cannot eliminate, or even reduce, the variation in flow and stability associated with a nonstandard or defective breaking head.

As illustrated in Figure 3, it is possible that a given mechanical hammer may not achieve the target bulk density obtained with a standard manual hammer. This may result from use of a nonstandard compaction pedestal, a nonstandard reaction (foundation), or some other variable.

A procedure called the "Penny Test" (Appendix C) has been used to evaluate pedestal reaction. The test consists essentially of placing a copper one cent piece in the mold and subjecting it to a total of 35 blows with the hammer. The penny is removed after every five blows, inspected, and replaced with a slightly different orientation. At the end of the test, a micrometer is used to determine the average diameter of the penny. The average diameter of nine pennies processed as above is considered a measure of pedestal reaction.

However, pedestal reaction is only one of several key variables that can influence compaction results. Also, different hammer characteristics, such as weight, flat foot, bevelled foot, etc., will result in different measures of pedestal reaction. Therefore, a measure of pedestal reaction alone cannot be used to calibrate the Marshall hammer.

Based on the literature review and results of the telephone interviews, the research team has concluded that a practical and reliable procedure and/or equipment for calibrating the Marshall apparatus is currently not available.

Table 7. Characteristics of mechanical hammers [4].

LAB NO.	MASS OF HAMMER(S)-kg	DROP OF HAMMER(S)-mm	THICKNESS OF COMPACTION FOOT-mm	TRADE NAME TYPE	MECH. BLOWS USED	MECH. DENSITY
1	4.54	457	15.9-17.4	HUMBOLDT/DOUBLE	60	2.411
2	4.54	470	10	MARSHALL/DOUBLE	75	2.377
3	4.50	457	13.0-15.0	MARSHALL/DOUBLE	60	2.421
4	-	-	-	-	-	-
5	4.54	457	11.3-14.4	HUMBOLDT/TRIPLE	60	2.443
6	4.57	456	16	HUMBOLDT/SINGLE	60	2.388
7	4.54	457	11.5-13.5	UNKNOWN	60	2.393
8	4.49	459	6.0-12.0	M&L	76	2.407
9	4.54	457	12	MARSHALL/?	63	2.454
10	4.53	457	12.0-18.0	MARSHALL/DOUBLE	60	2.408
11	4.54	453	FLAT	PINE INST./?	75	2.421
12	4.54	457	5.0-12.0	M&L	75	2.419
13	4.53	457	12.6-15.2	HUMBOLDT/DOUBLE	50	2.380
14	4.50	457	6.5-9.5	REINHART	75	2.390
15	4.51	455	10.2-14.2	REINHART	75	2.437
16	4.68	457	25.4	SOILTEST/SINGLE	80	2.439
17	4.54	457	11.0-14.0	MARSHALL	70	2.454
18	-	-	-	HUMBOLDT	60	2.319
19	-	-	-	-	-	-
20	-	-	-	-	-	-
21	4.54	457	12.0	SOILTEST/?	75	2.374
22	4.54	442	19.0-79.0	HOMEMADE	75	2.429
23	-	-	-	-	-	-
24	4.70	456	19.3-19.4	MARSHALL/DOUBLE	61	2.403
25	-	-	-	-	-	-
26	-	-	-	-	-	-
27	4.55	457	12.3-14.9	HUMBOLDT/DOUBLE	60	2.444
28	4.53	456	12.0			
	4.58	454	12.0	HOMEMADE	100	2.418
	4.56	450	12.0			
29	4.70	453	11.0	HOMEMADE	75	2.376
30	-	-	-	-	-	-
31	-	-	-	-	-	-
All Data						
n	24	24				
Mean	4.55	456				
St.Dev.	0.06	4				
Data Range	4.49-4.70	442-470				
ASTM	4.54	454				

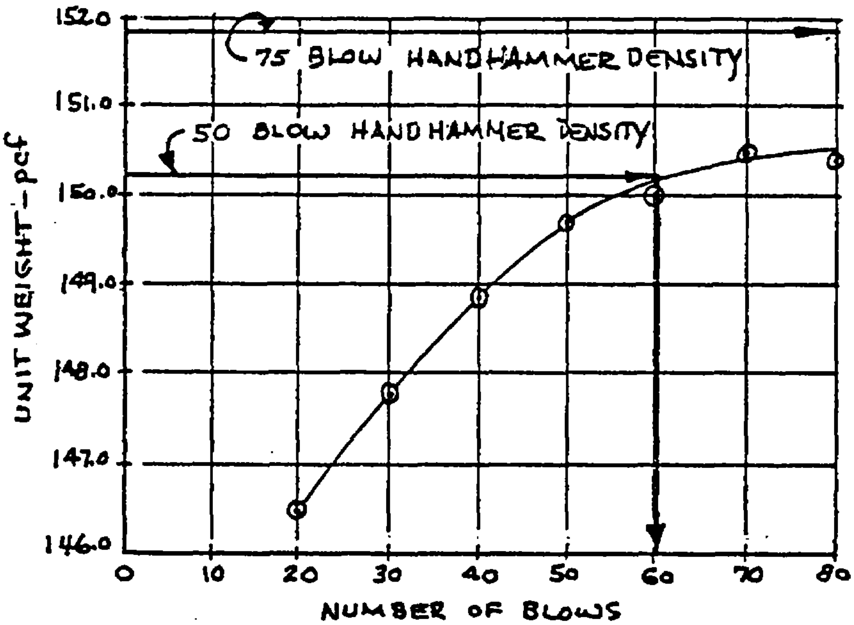


Figure 3. Procedure for calibrating a mechanical hammer.

TASK 3. PRELIMINARY EXPERIMENTAL EVALUATION

To examine the ability to measure the fundamental process parameters of the Marshall hammer operation, an experiment was performed in the Materials Testing Laboratory at the Pennsylvania Transportation Institute. The study was designed to explore the possibility of obtaining meaningful process information with a limited amount of instrumentation and sophistication, and was not intended to be a comprehensive experimental evaluation of the compaction process.

The test consisted of instrumenting a mechanical Marshall compaction hammer with three accelerometers and recording the impact time histories from 15 asphalt samples on an FM tape recorder. The tape recordings of the accelerations were then analyzed by applying some rudimentary digital signal processing techniques. Through interpretation of the data, several conclusions with regard to the compaction process and the associated variables can be made. In addition, this preliminary evaluation formed the foundation for recommending further experimental testing and the instrumentation required to examine the process variabilities between different compaction hammers.

The following sections first describe the experimental procedure and data acquisition procedure. Next, the analyzed data are presented and interpreted with respect to the hammer evaluated. Finally, guidelines for further tests and testing procedures are discussed.

Experimental Testing Procedure and Data Acquisition

The procedures for evaluating the Marshall compaction process paralleled techniques originally developed to examine hot-forging hammer operations [6]. The basic rationale consists of mounting shock accelerometers on the critical components of the hammer associated with the energy transfer. For the Marshall hammer, these components consist of the falling mass, the mold base plate, and the floor in the vicinity of the hammer installation. The accelerometers are orientated in the vertical direction to measure the energy transfer of the hammer's structural members during the compaction impact. All of the acceleration data were recorded on a multichannel FM tape recorder to facilitate later analysis. The tape recording approach allows the personnel to concentrate on the acquisition of valid data during the actual testing, and not on its immediate analysis. The instrumentation schematic used for the testing is illustrated in Figure 4. Photographs of data collection instrumentation and layout are shown in Figures 5 and 6.

PCB Piezotronics model 305A shock accelerometers were mounted to measure the falling mass and base plate accelerations. The actual locations of the transducers are shown in Figures 7 and 8. The 305A accelerometers have a maximum acceleration limit of 5000 g's and are well-suited to this application. A PCB 302A general purpose accelerometer was mounted on the floor next to the Marshall hammer. The accelerometer mounted on the falling mass is the most critical equipment for characterizing the compaction impact and also the most difficult to install. An appropriately sized hole was drilled and tapped on the top face of the hammer. The integral threaded stud on the accelerometer housing was then screwed into this hole to secure the accelerometer. The accelerometer was also epoxied to the hammer to avoid possible loosening during the impacts. Special installation techniques had to be utilized to allow the accelerometer cable to move vertically 18 inches and withstand the high acceleration levels. This capability was accomplished by allowing the cable to move freely between the falling mass and a point fixed in front of the hammer. The fixed point was provided by forming an inverted Y with nylon string attached to surrounding structures. A photograph of this arrangement is shown in Figure 9.

The three channels of acceleration data were recorded on a TEAC MR 10 four-channel FM recorder. The frequency modulation recording technique sacrifices the high-frequency (above 5 KHz) response for the ability to record low-frequency data (capable of DC). The spectral content of transient phenomona dictates that this trade-off be made. While recording, the data were simultaneously monitored on an AT&T PC6300 with a Computational Systems Inc. Wavepak data acquisition system. The Wavepak system allows the microcomputer to emulate a digital oscilloscope and dual channel FFT analyzer. The digital data mode, with its inherent pretrigger data-capture capability, is critical to the analysis of this short-time-duration phenomenon.

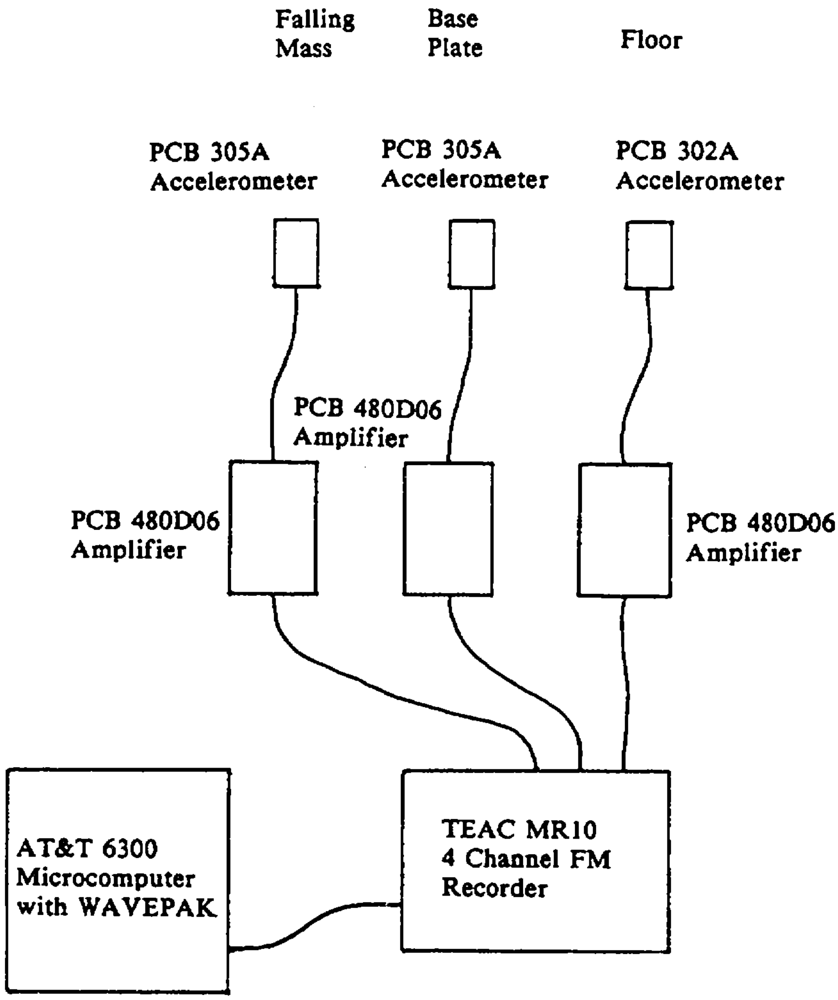


Figure 4. Instrumentation schematic for Marshall hammer data collection.

Figure 5. Test site overview showing instrumented Marshall hammer and test equipment.

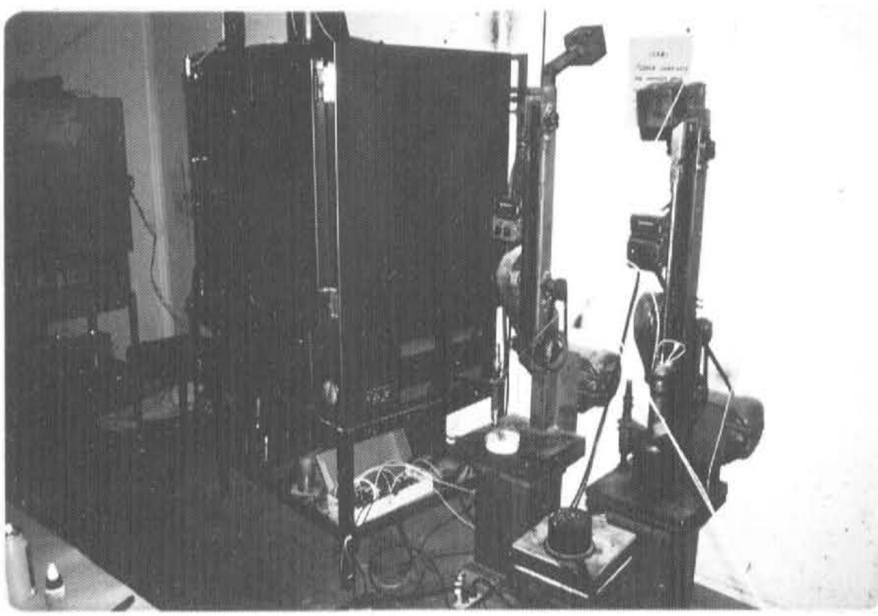


Figure 6. Instrumented Marshall hammer and furnaces.

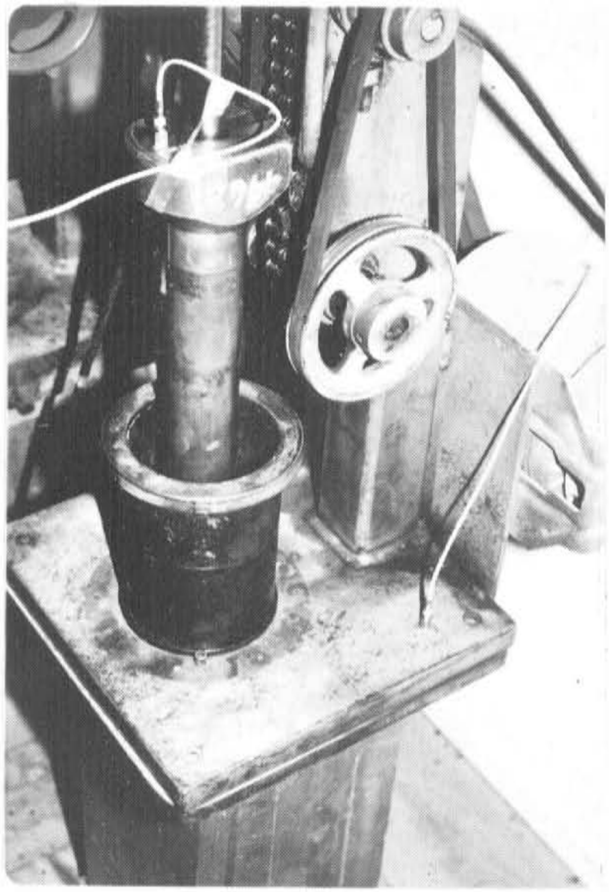


Figure 7. The mounting locations of the falling mass and base plate accelerometers on the test hammer.

Figure 8. Close-up of the falling mass accelerometer.

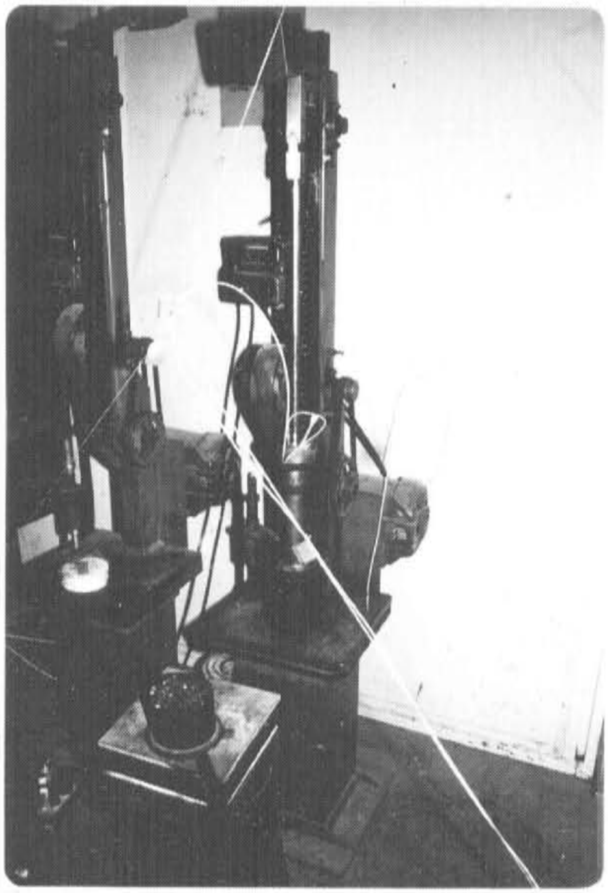


Figure 9. Photograph of the falling mass accelerometer cable mounting system.

The data collection phase commenced with representative impacts of the hammer to ensure that the gain settings on all of the instrumentation were adjusted to the appropriate levels. Acceleration data were then recorded for a total of 15 samples, with 35 blows on each side. Pennsylvania's ID-2 wearing course mix was used for the study. The composition of the mix is shown in Table 8. The basic testing procedure followed the ASTM standard for hand hammers as closely as possible. The sample temperatures were targeted at 280°F. Data from several samples were lost when the cable from the base plate accelerometer became loose. Acceleration data from a total of 10 samples were recorded and judged to be adequate for further analysis.

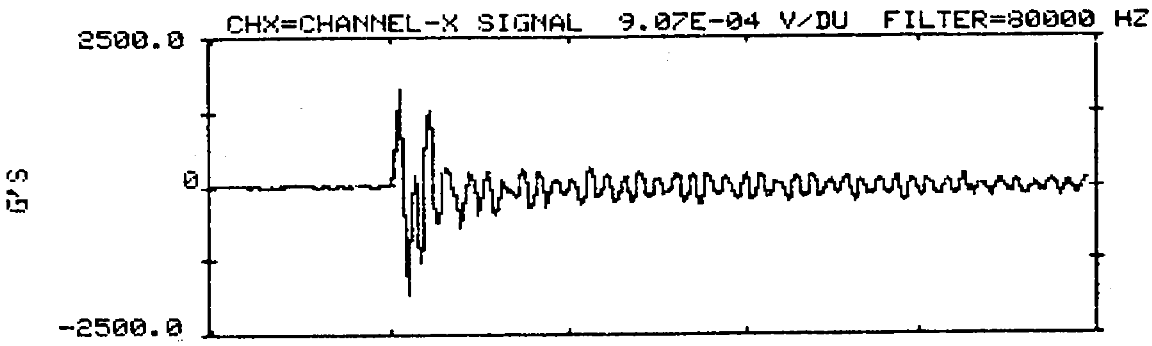
Analysis of Marshall Hammer Acceleration Data

The tape recorded data were further analyzed by utilizing the digital processing capabilities of the AT&T microcomputer and Wavepak system. After determining the appropriate playback gain calibration factors, the representative acceleration time histories for the three channels were captured and analyzed by using several different approaches.

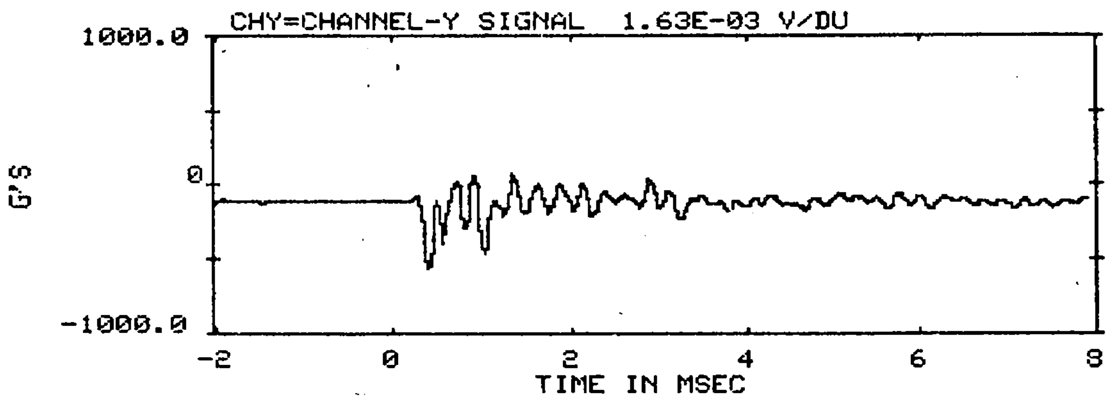
Figure 10 illustrates typical acceleration signals from the three channels recorded. The falling mass acceleration shows that the impact has a very short duration of around 1 ms and has a peak acceleration of greater than 2,000 g's. The impact excites the longitudinal vibration modes of the falling mass, which appears as the longer duration ringing in the signal. The actual deformation impact is not clearly apparent from the acceleration signal because of the structural ringing. The base plate acceleration is shown in Figure 10. The acceleration basically shows only the structural ringing of the base plate with peak levels less than 250 g's. Figure 10 also shows the acceleration measured on the floor next to the hammer installation; the signal shows a significant acceleration pulse on the order of 25 g's. The high level of the floor's response to the impact is indicative of the energy flow away from the hammer and not into the sample. This indicates the possible major role of the hammer installation in the variability of results from separate facilities.

Table 8. Composition of mix used in the study.

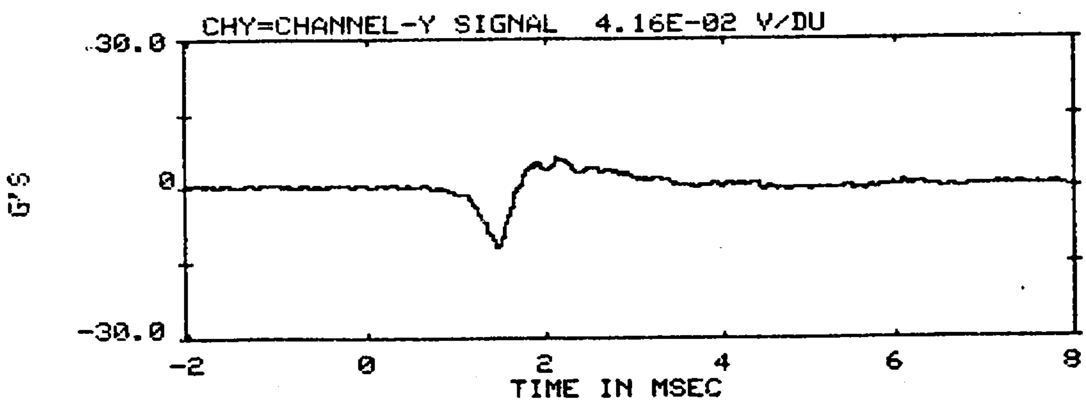
Gradation		Asphalt Cement
Sieve Size	Percent Passing	
1/2"	100	AC-20 at 6% by weight of mix
3/8"	95	
No. 4	67	
No. 8	40	
No. 16	24	
No. 30	15	
No. 50	10	
No. 100	8	
No. 200	6	



Falling mass acceleration.



Base plate acceleration.



Floor acceleration.

Figure 10. Acceleration signals from a typical impact.

Figures 11 through 20 compare the falling mass acceleration signals for every seventh blow from three different samples. The signals confirm the expected amount of variability between the blows; however, the trends are similar between each sequence. The blow strength tends to become greater as the sample becomes more compacted in the later blows. In an effort to more quantitatively examine the repeatability of the hammer process, the energy autospectrum of the falling mass acceleration was estimated for three samples by considering every fifth blow in the sequence. Signal triggering difficulties made this a time-consuming process and prevented the spectrum from being ideally estimated using all 70 impacts. The three spectra are shown in Figures 21, 22, and 23. The spectra are similar, with slight variations among them. The integral of the area under the spectra curve is proportional to the energy imparted to the sample. Within the tolerance permitted by this experiment, the area under the three curves can be judged to be equivalent. This situation indicates that a significant degree of process repeatability exists between samples tested using the same hammer. Figures 24, 25, and 26 present the spectra estimated from the base plate acceleration for the same sequence of events as that analyzed for the spectra in Figures 21 through 23. The similarity of these spectra is, again, an indication of the repeatability of the compaction process.

The deformation energy imparted to the sample can be calculated from the interpretation of the acceleration signals. However, it is apparent from Figures 11 through 20 that the structural ringing in the signals is sufficiently strong to preclude a direct measurement. In an effort to extract this data, a low-pass electrical filter was introduced to eliminate the high-frequency ringing. Figures 27, 28, and 29 illustrate typical acceleration time histories with and without a filter. After some experimentation, it was found that a filter with a cutoff between 1 kHz and 2 kHz provided the best response. The filter does eliminate the ringing, but it also modifies the signal. Unfortunately, this distortion is sufficient to preclude accurate estimation of the impact energy. With further experimentation, however, the proper filter combination could be determined and calibrated to accurately estimate impact energy from data of this type.

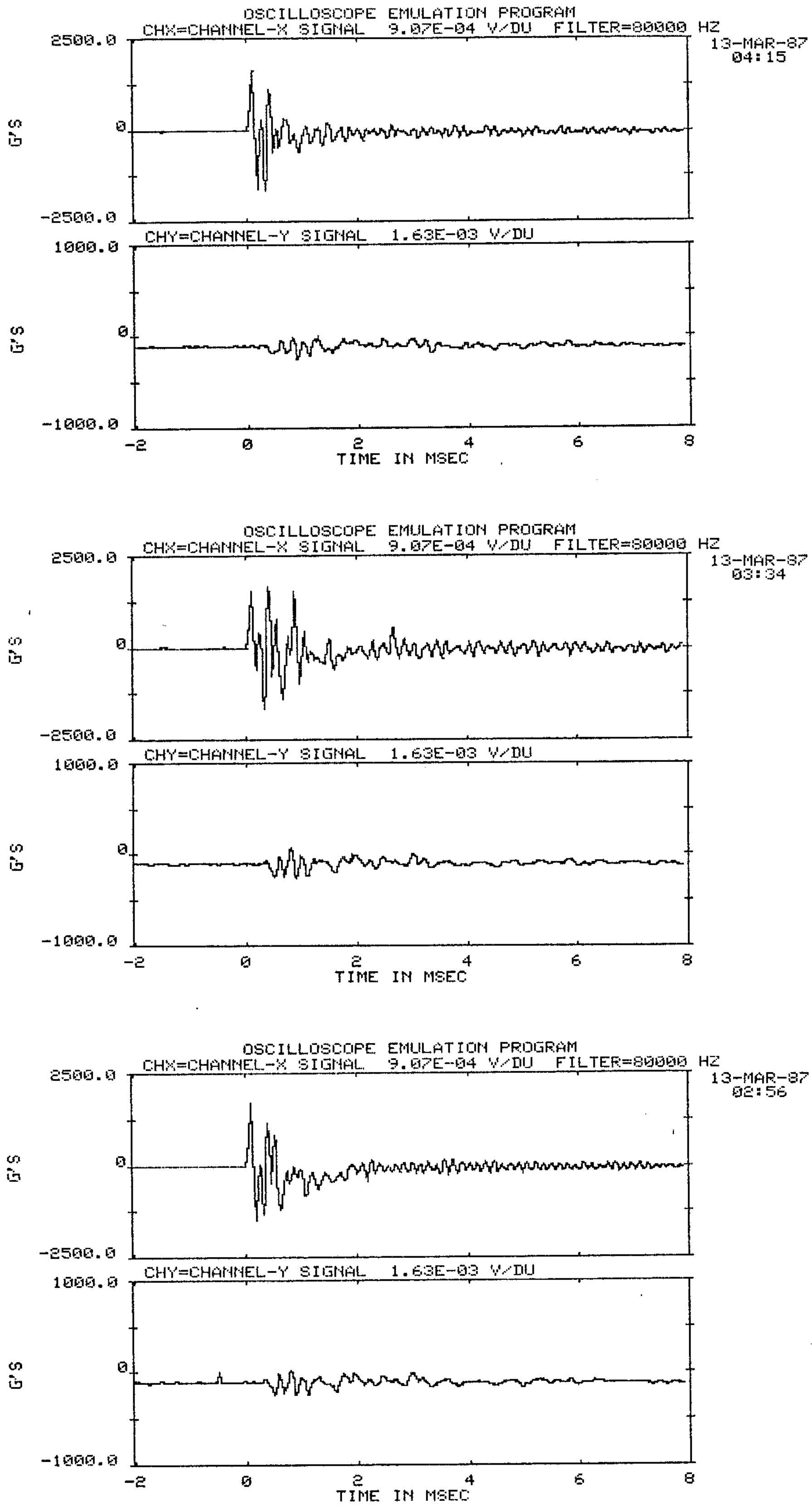


Figure 11. Falling mass and base plate accelerations from every seventh Blow in a typical Marshall hammer sequence for three different asphalt specimens (Top curve is the falling mass acceleration and bottom curve is the base plate acceleration)--blow 7, side 1.

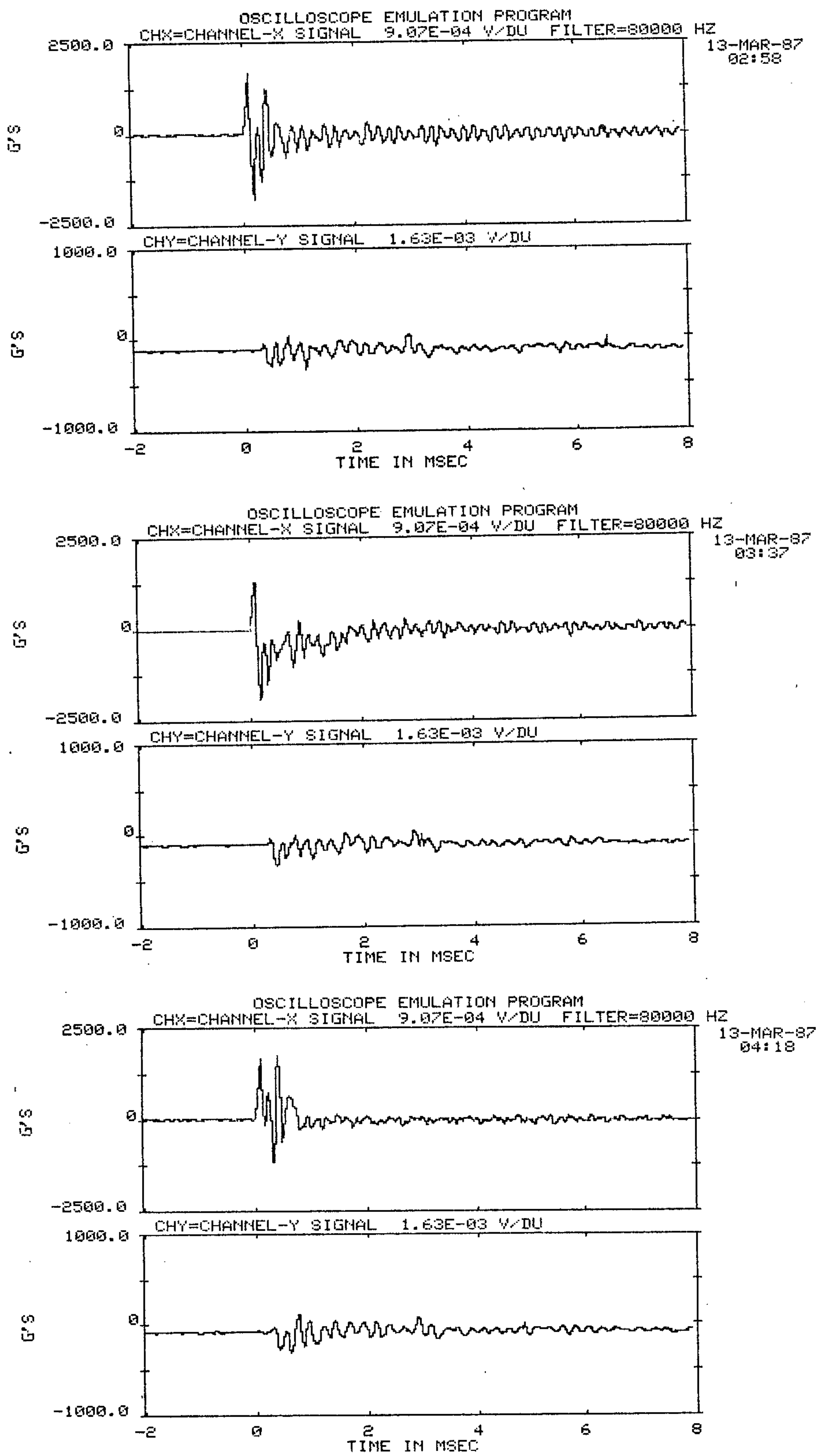


Figure 12. Falling mass and base plate accelerations from every seventh blow in a typical Marshall hammer sequence for three different asphalt specimens (Top curve is the falling mass acceleration and bottom curve is the base plate acceleration)--blow 14, side 1.

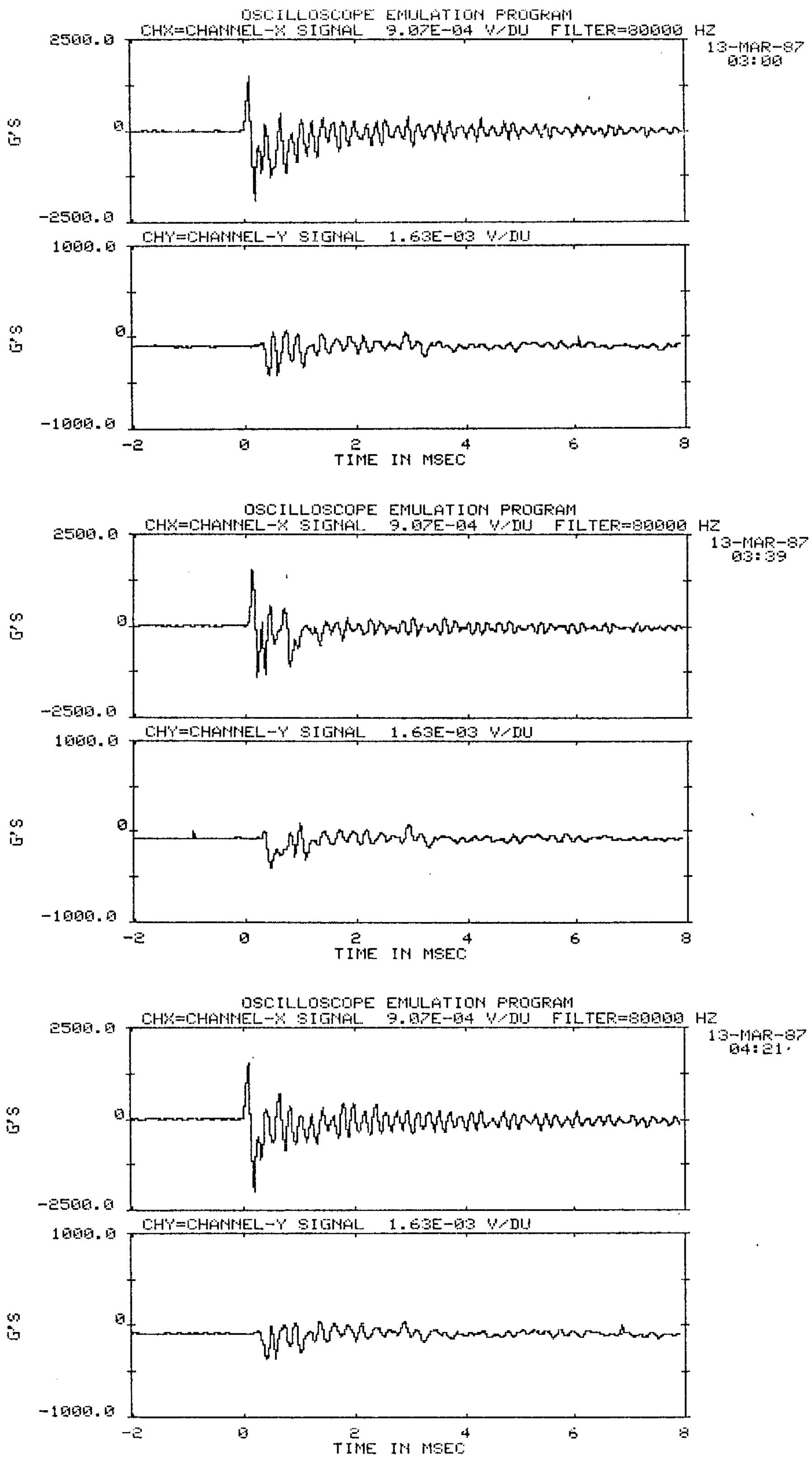


Figure 13. Falling mass and base plate accelerations from every seventh blow in a typical Marshall hammer sequence for three different asphalt specimens (Top curve is the falling mass acceleration and bottom curve is the base plate acceleration)--blow 21, side 1.

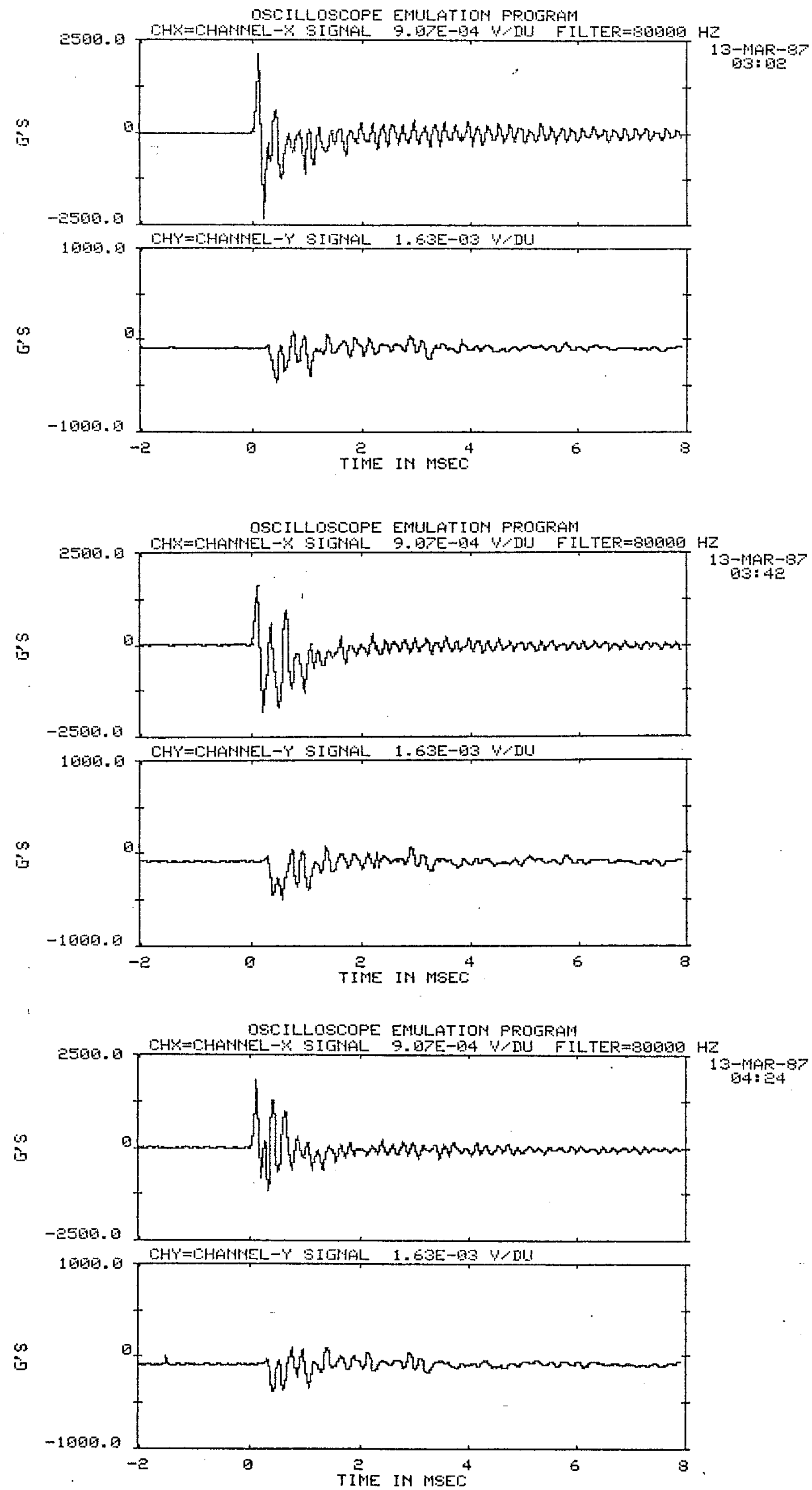


Figure 14. Falling mass and base plate accelerations from every seventh blow in a typical Marshall hammer sequence for three different asphalt specimens (Top curve is the falling mass acceleration and bottom curve is the base plate acceleration)--blow 28, side 1.

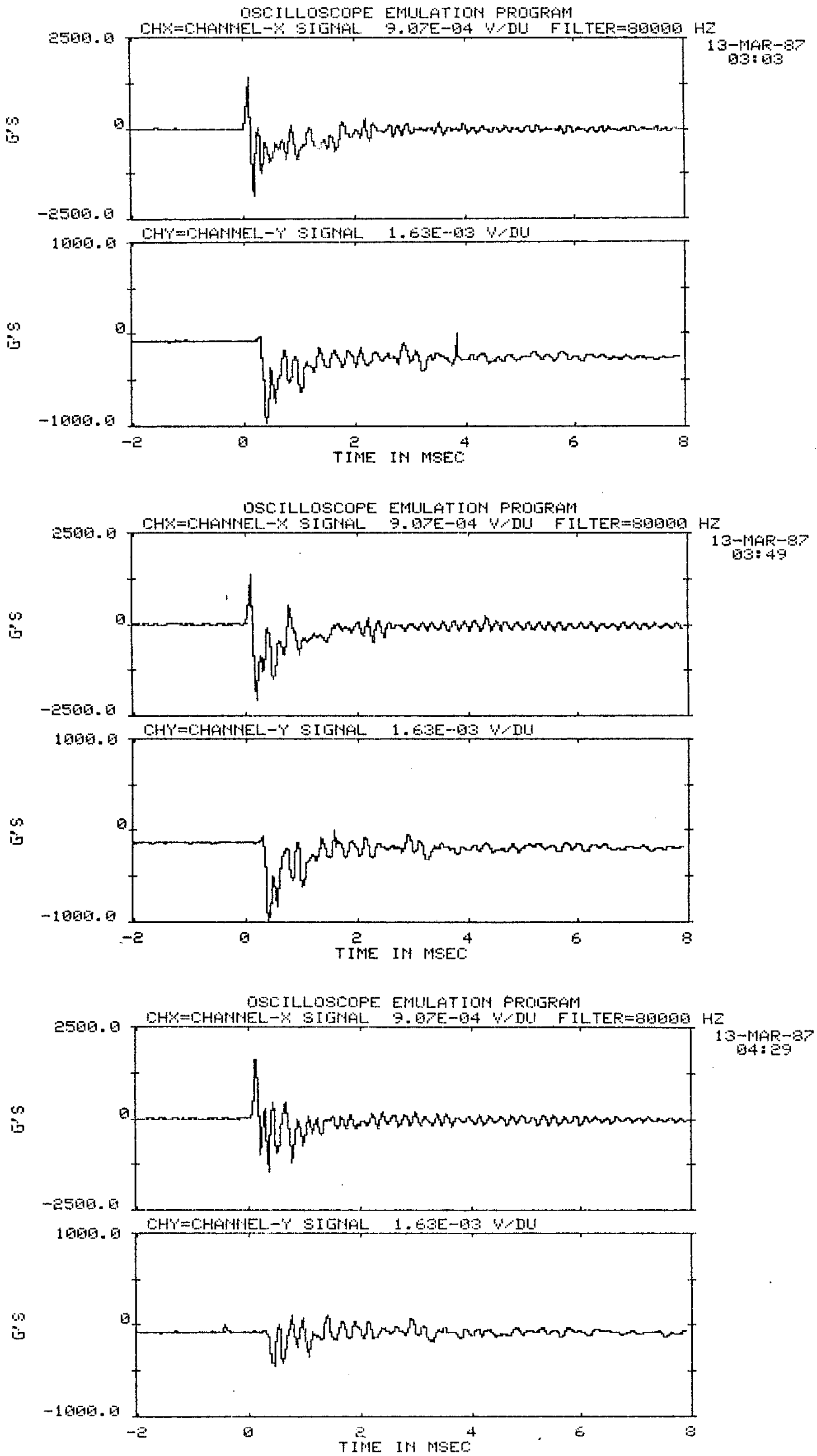


Figure 15. Falling mass and base plate accelerations from every seventh blow in a typical Marshall hammer sequence for three different asphalt specimens (Top curve is the falling mass acceleration and bottom curve is the base plate acceleration)--blow 35, side 1.

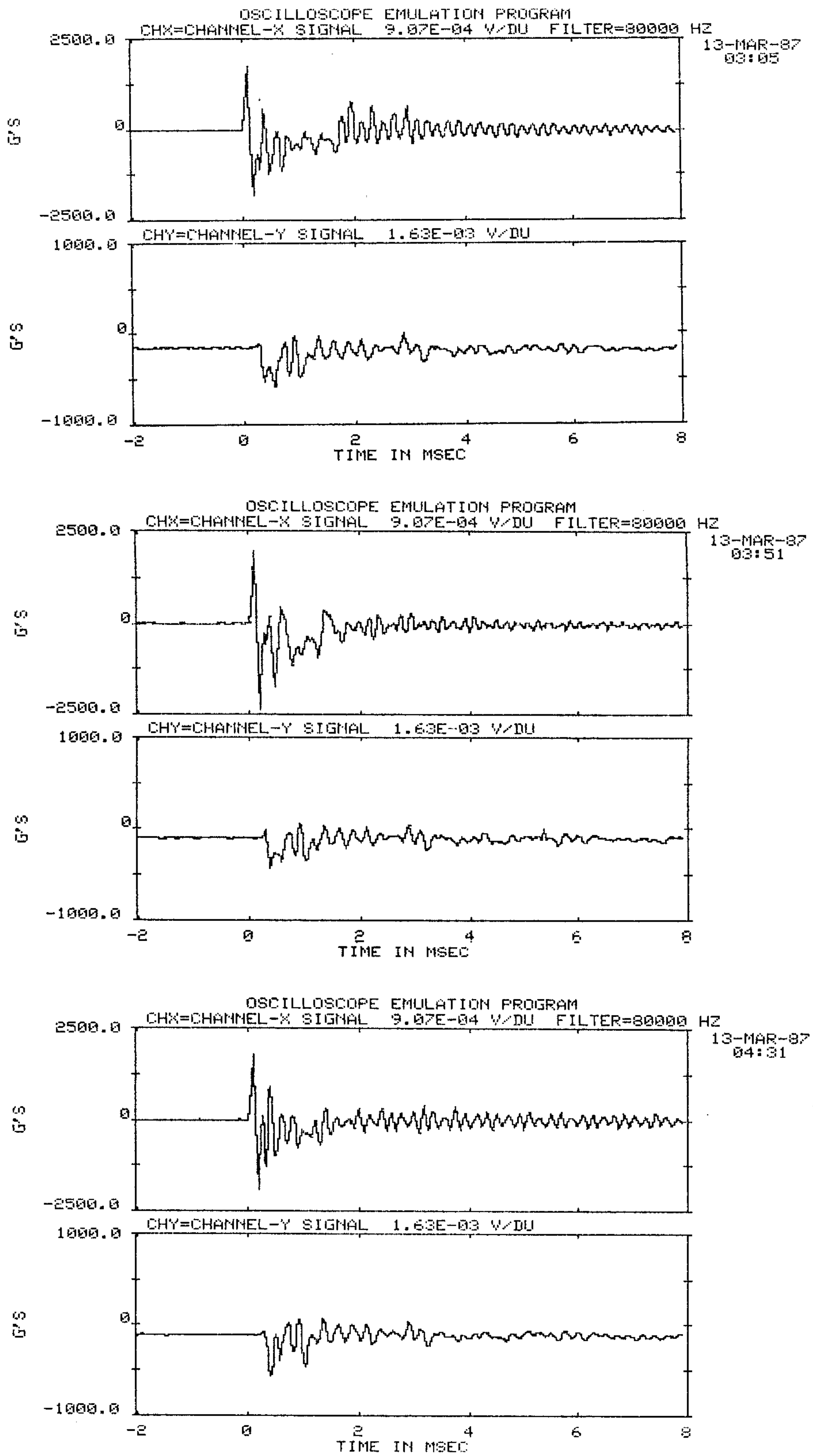


Figure 16. Falling mass and base plate accelerations from every seventh blow in a typical Marshall hammer sequence for three different asphalt specimens (Top curve is the falling mass acceleration and bottom curve is the base plate acceleration)--blow 7, side 2.

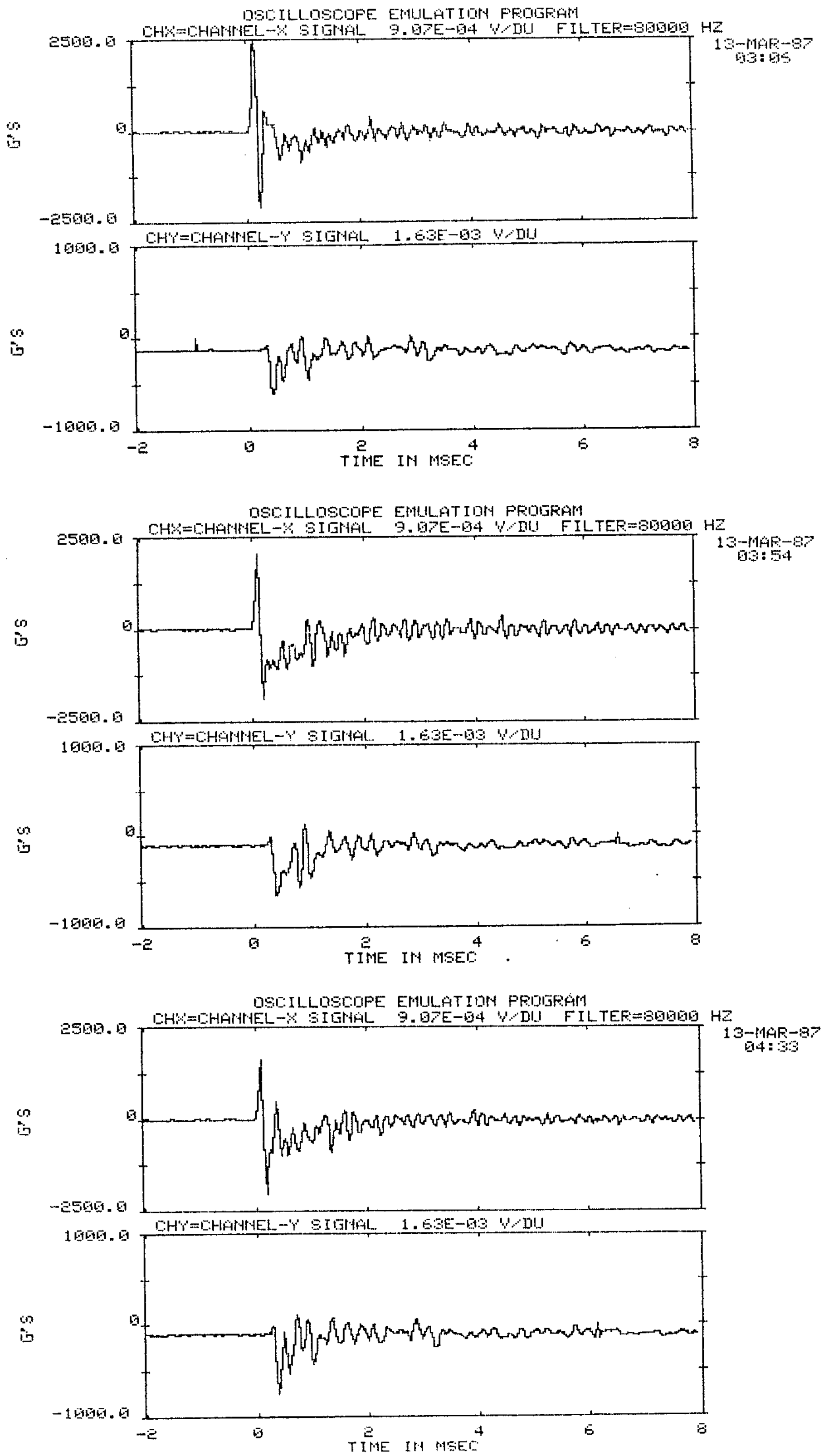


Figure 17. Falling mass and base plate accelerations from every seventh blow in a typical Marshall hammer sequence for three different asphalt specimens (Top curve is the falling mass acceleration and bottom curve is the base plate acceleration)--blow 14, side 2.

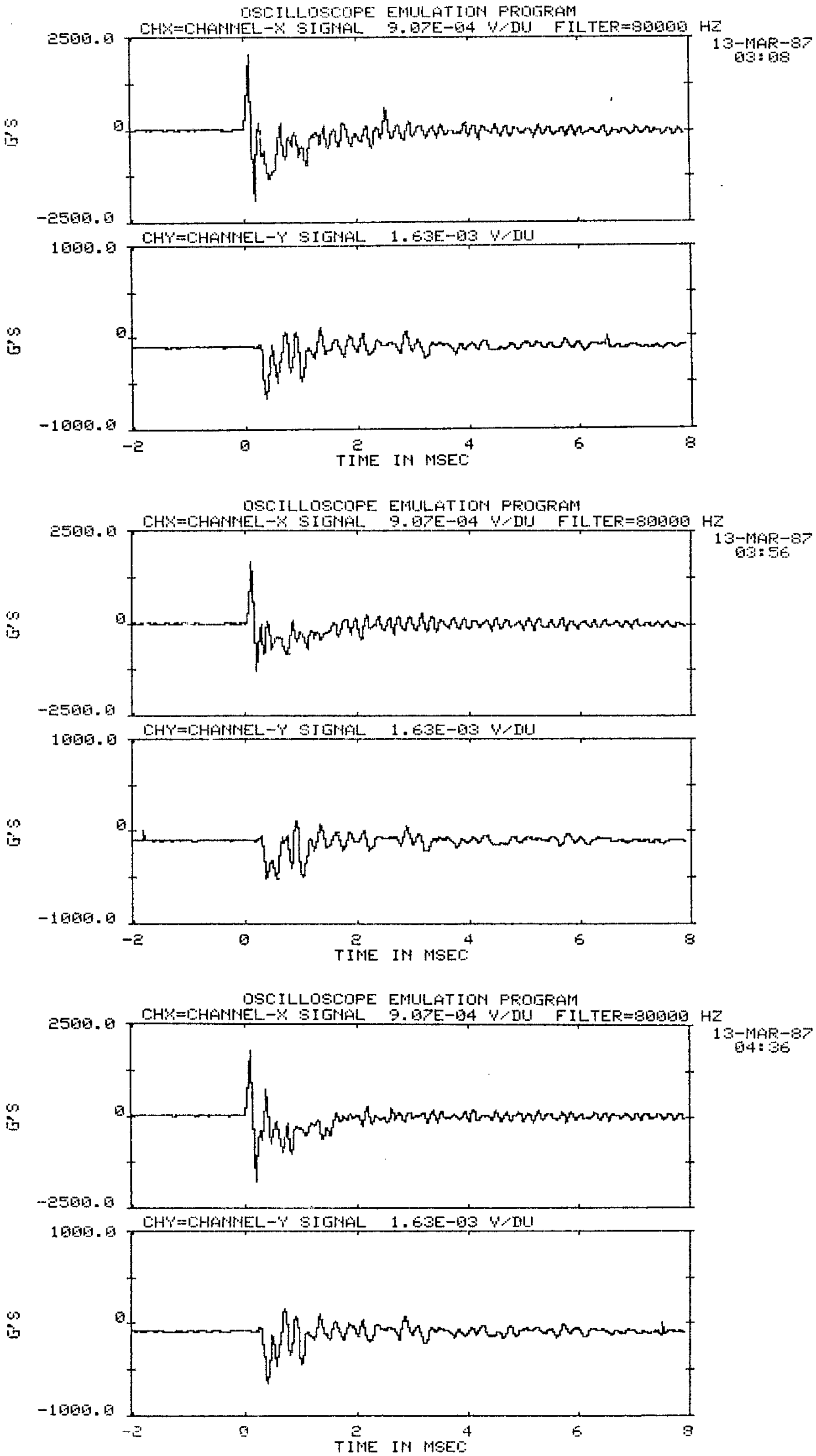


Figure 18. Falling mass and base plate accelerations from every seventh blow in a typical Marshall hammer sequence for three different asphalt specimens (Top curve is the falling mass acceleration and bottom curve is the base plate acceleration)--blow 21, side 2.

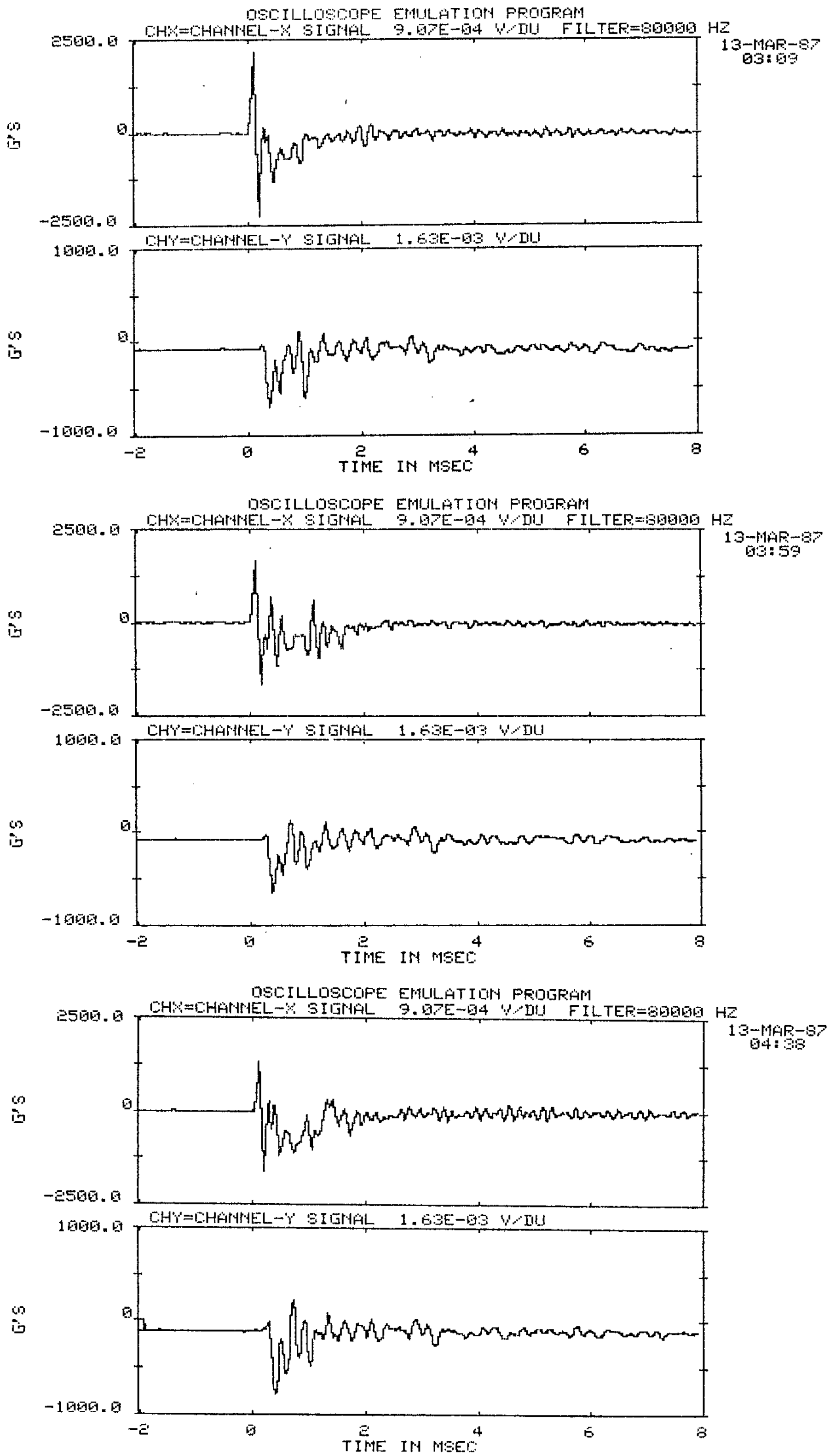


Figure 19. Falling mass and base plate accelerations from every seventh blow in a typical Marshall hammer sequence for three different asphalt specimens (Top curve is the falling mass acceleration and bottom curve is the base plate acceleration)-- blow 28, side 2.

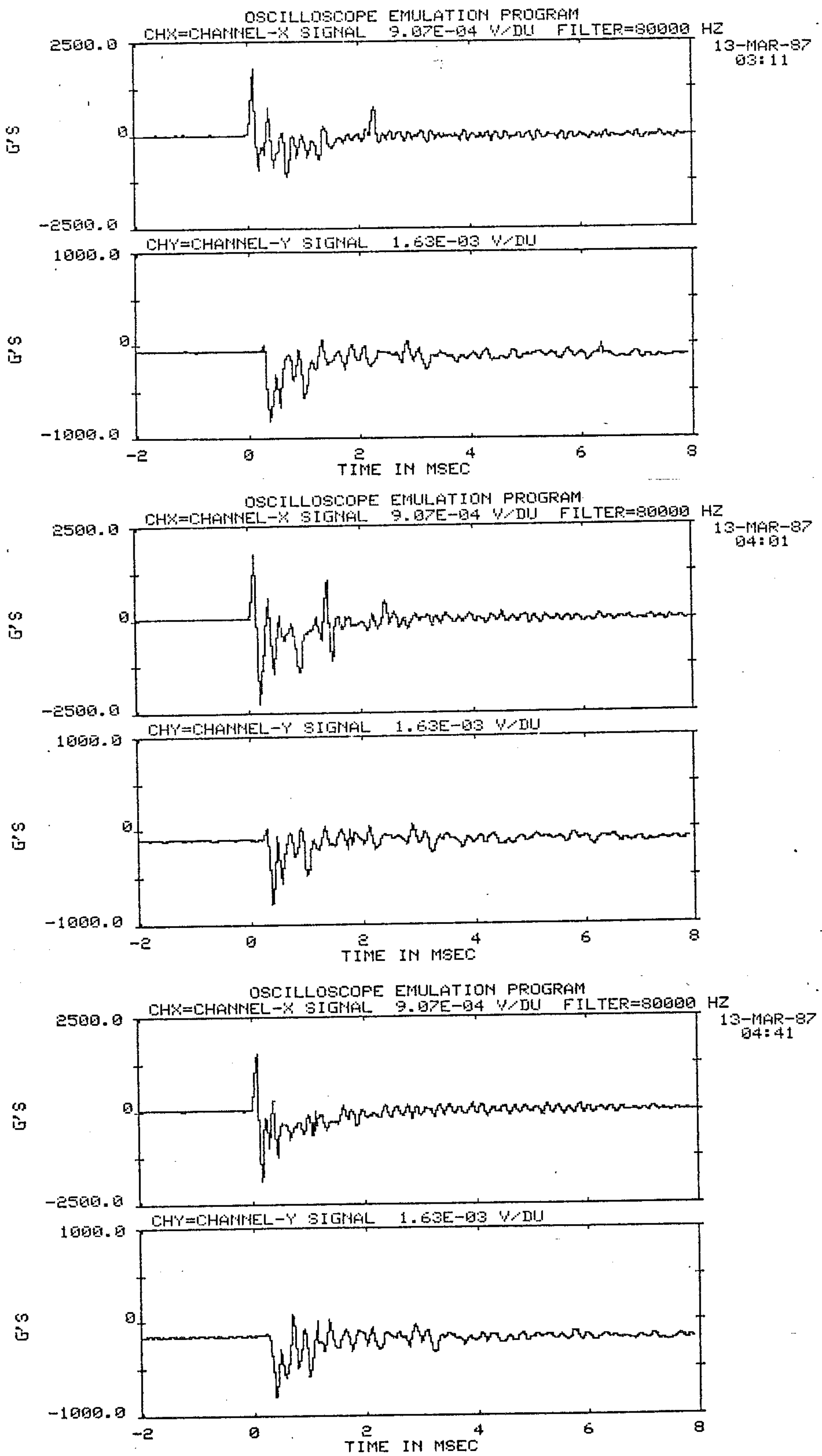


Figure 20. Falling mass and base plate accelerations from every seventh blow in a typical Marshall hammer sequence for three different asphalt specimens (Top curve is the falling mass acceleration and bottom curve is the base plate acceleration--blow 35, side 2.

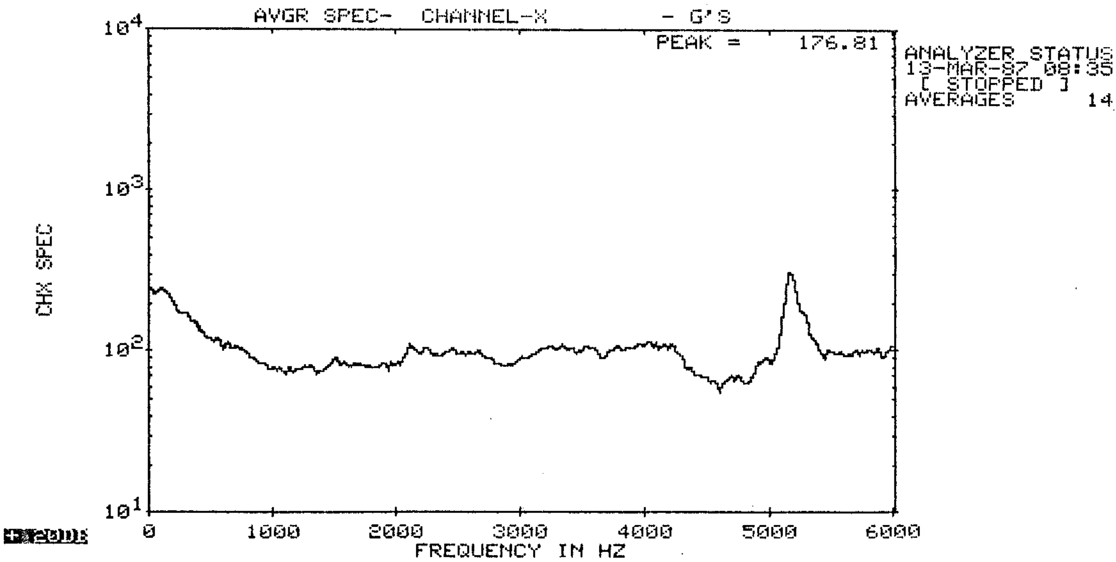


Figure 21. Falling mass acceleration autospectrum, estimated from the time signal shown in Figures 11-20, specimen 1.

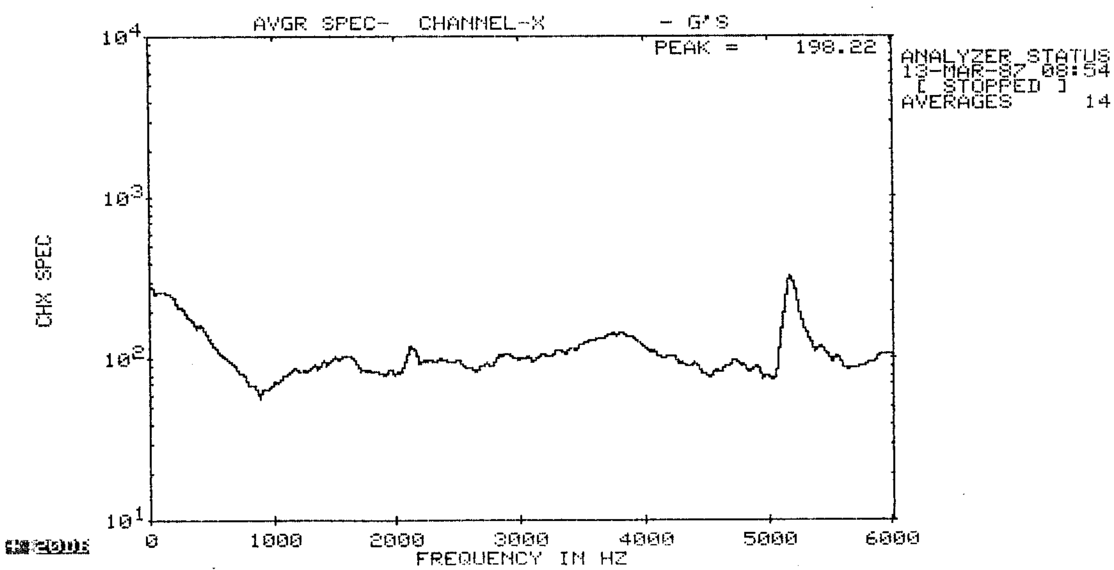


Figure 22. Falling mass acceleration autospectrum, estimated from the time signal shown in Figures 11 through 20, specimen 2.

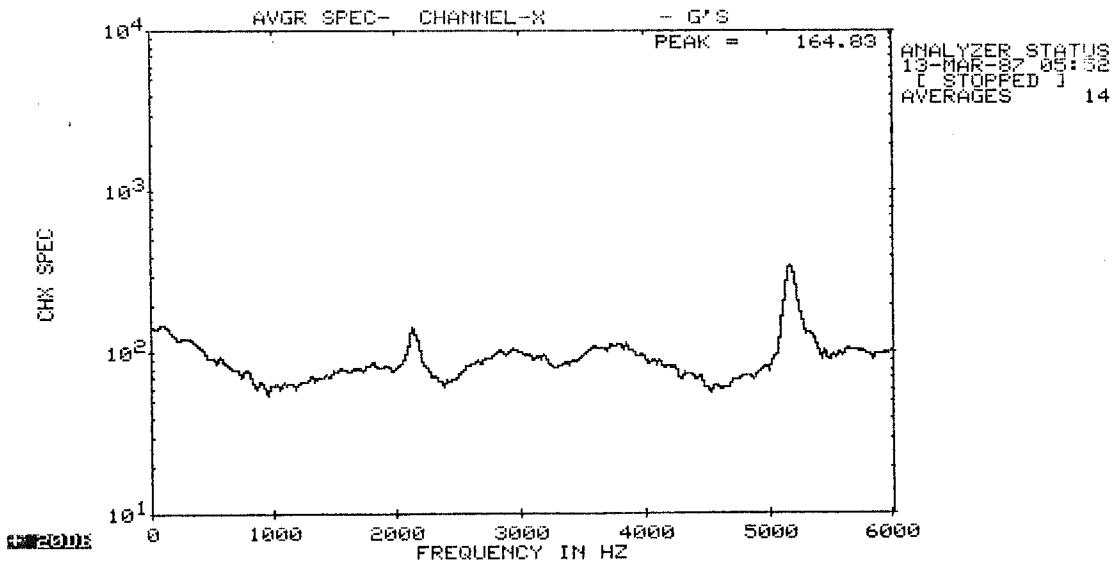


Figure 23. Falling mass acceleration autospectrum, estimated from the time signal shown in Figures 11-20, specimen 3.

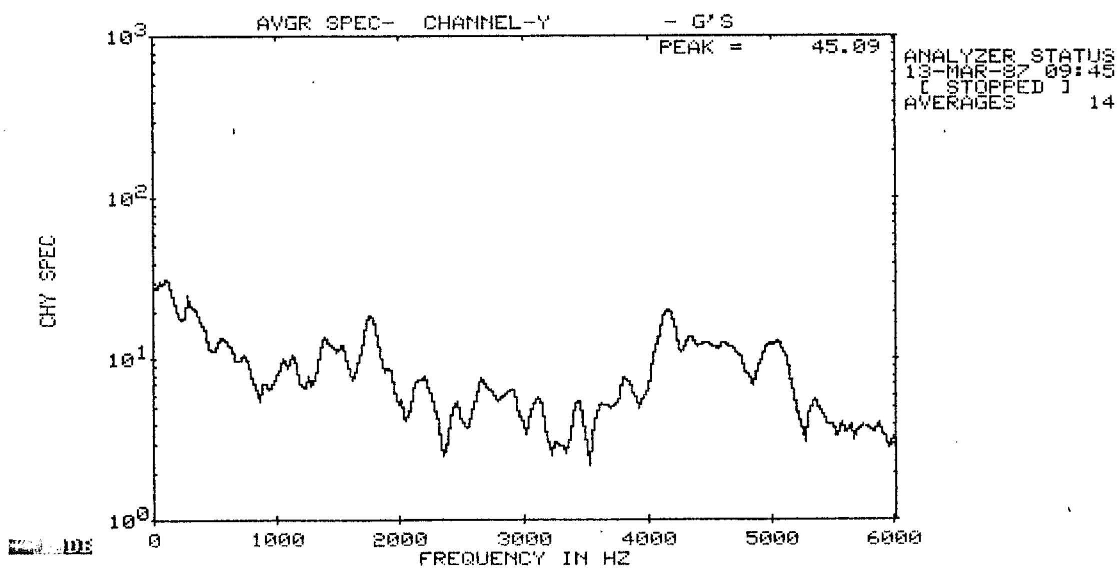


Figure 24. Base plate acceleration autospectrum, estimated from the time signal shown in Figures 11-20, specimen 1.

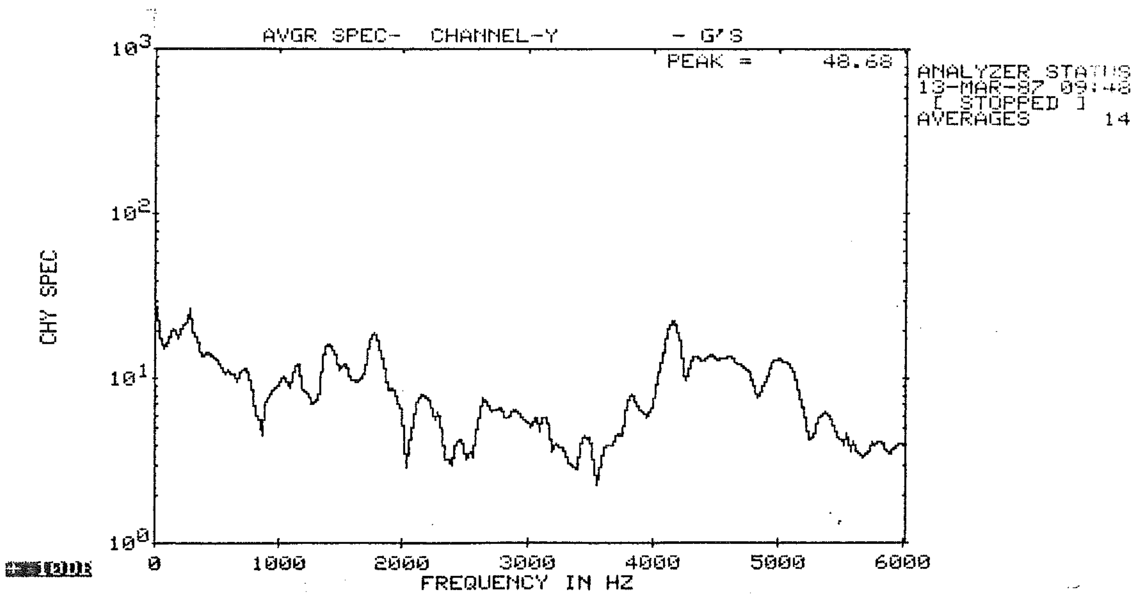


Figure 25. Base plate acceleration autospectrum estimated from the time signal shown in Figures 11 through 20, specimen 2.

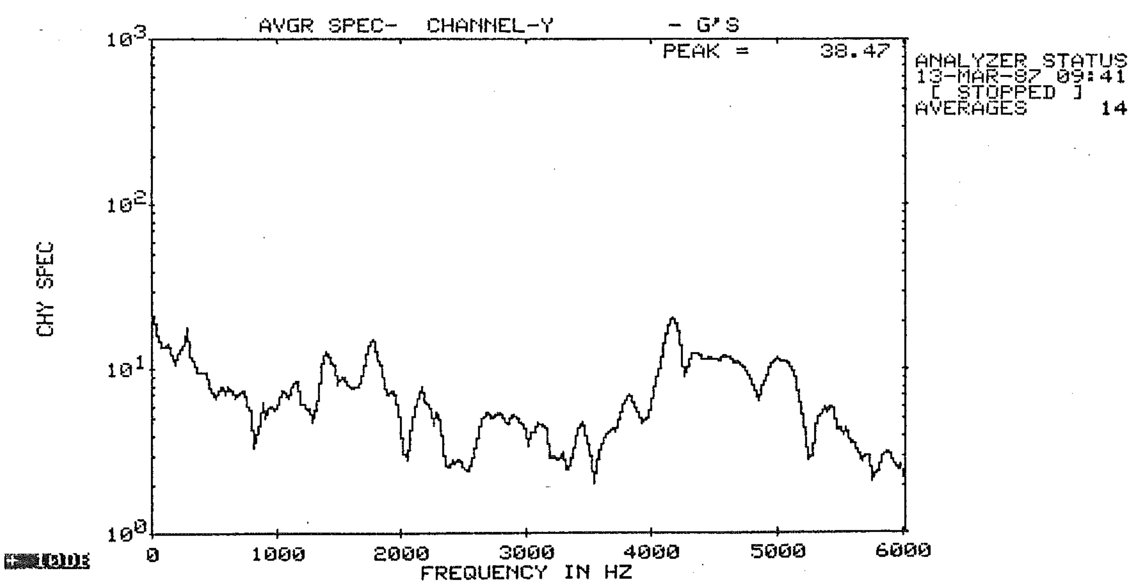


Figure 26. Base plate acceleration autospectrum, estimated from the time signal shown in Figures 11 through 20, specimen 3.

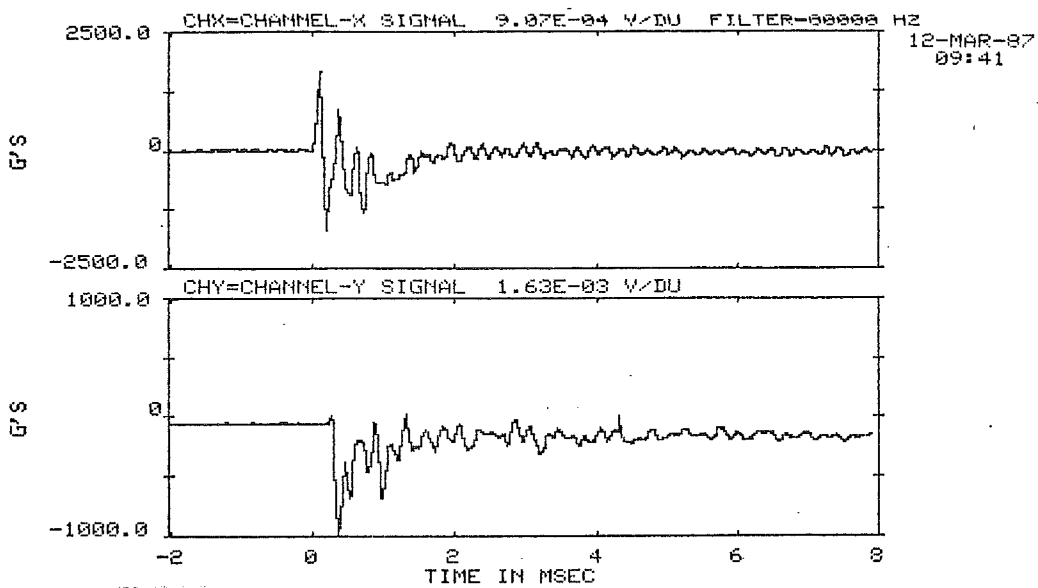


Figure 27. Falling mass acceleration time history with no filter.

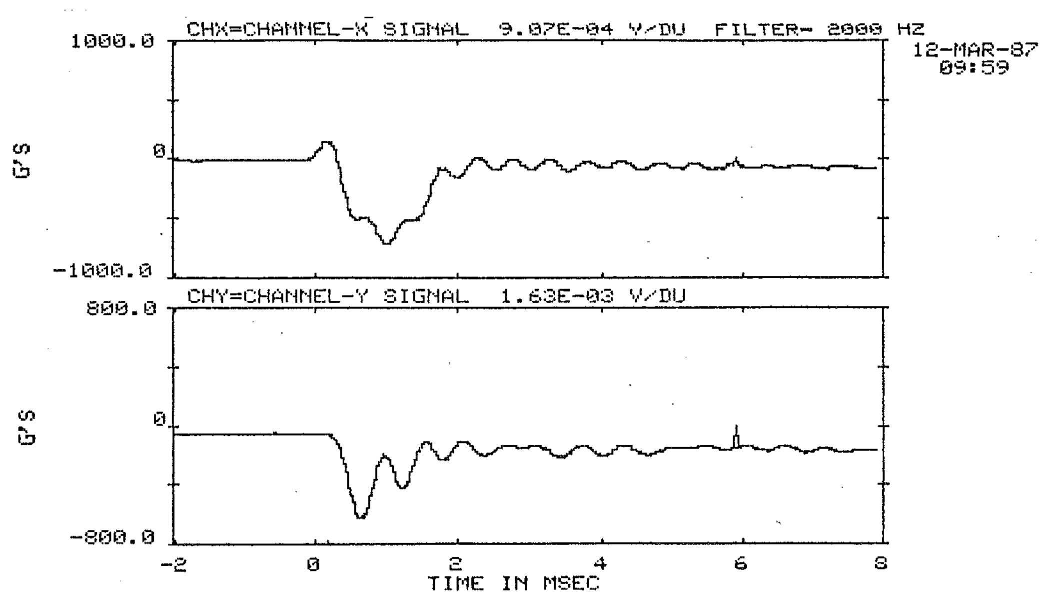


Figure 28. Falling mass acceleration time history with 2kHz low-pass filter.

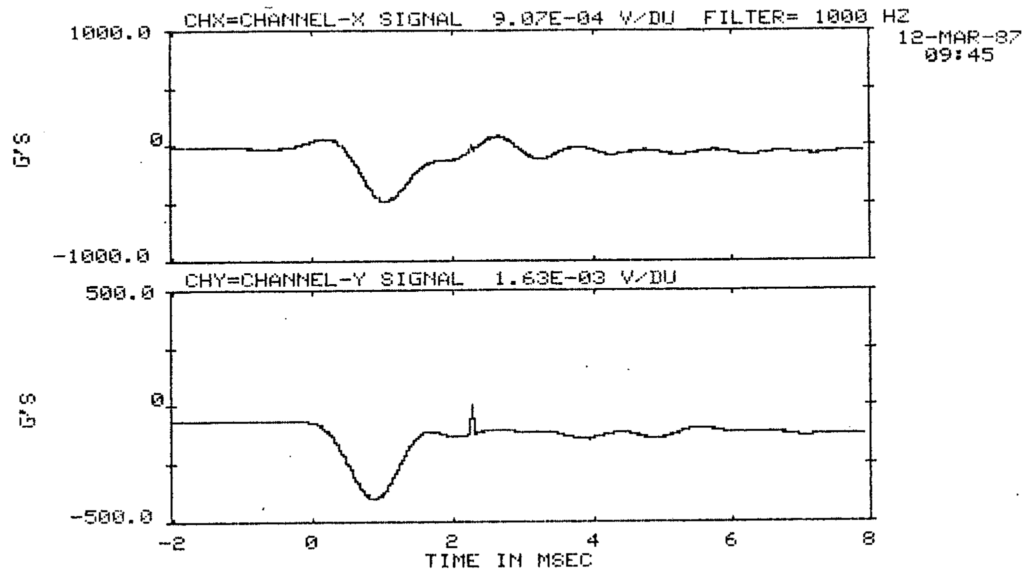


Figure 29. Falling mass acceleration time history with 1-kHz low-pass filter.

Discussion of the Test Results

From the experiment performed, several conclusions can be made with regard to the hammer and compaction process. These are outlined as follows:

1. The compaction process is repeatable for the specimens prepared on the hammer used in the study. Random variations that occur during the impacts, such as changes in the rod friction, misalignment of the mold, and mold friction, appear not to affect the process.

2. The hammer installation appears to be critical. The acceleration levels recorded indicate a significant interaction with the surrounding support structure. This indicates that the relative stiffness of the supporting floor could cause variations in the compaction process and, hence, affect the test results.

3. Reliable process information can be extracted from the hammer with relatively simple instrumentation. The structural ringing makes it difficult to extract the deformation impact from the rest of the signal. Filtering reduces the ringing effect but colors the resulting signal. This distortion makes it difficult to estimate the actual impact energy, but, nevertheless, the signal can be used for comparison purposes.

4. For the hammer evaluated, the impact consisted of a single blow with no repetitive bounces resulting from rebound of the hammer head.

Recommendations for Developing a Field Calibration Procedure

As previously discussed, the characteristics of the compaction hammer are only one potential cause of variation in Marshall test results. With an appropriately applied specification, these factors, such as hammer weight, free fall, friction between the rod and the hammer, and the mold restraint, can be minimized. In the same manner, many of the operator variables, such as hammer alignment (hand compaction), method of filling the molds, and compaction temperature, can also be minimized. In the preliminary laboratory study, Task 3, the base support was shown to be highly significant with regard to the amount of energy transmitted to the specimen during compaction. In addition, the type of compaction pedestal interacts with the base support in determining the amount of energy delivered to the specimen. Although no procedure or method exists for determining the amount of compaction energy delivered to the specimen, the appropriate technology does exist for developing such a method. The advantages of a field calibration procedure are several:

1. The characteristics of equipment manufactured by different vendors could be compared.

2. The interactions among the hammer characteristics, type of compaction pedestal, and base support can be compared.

3. The effect of operator variables in determining compaction density can be compared and separated from equipment-installation variables.

Therefore, further research to develop the specialized equipment procedures that may be used to calibrate the various field hammers against a specified standard is warranted. The necessary research may be subdivided into three subtasks, as indicated below:

<u>Task A--Test equipment development</u>. Previous work has demonstrated the feasibility of measuring the impact energy with accelerometers mounted to the hammer's structure. This approach suffered from the inclusion of the structural ringing in the signals and the difficult application of the accelerometers to the hammer. This research should be directed at developing a simple and easily utilized transducer to measure the compaction force history imparted to a test specimen. It is recommended that the transducer be placed between the specimen mold and the Marshall hammer base plate. The transducer should have the following characteristics:

1. Rugged construction.
2. Adequate sensitivity and frequency response, without overloading during the peak impact.
3. Insensitivity to temperature variations.

4. Capability of operation between temperatures of 100 and 300°F.
5. Low profile (less than 1/2 inch).
6. Voltage output directly proportional to units of force.
7. Self-contained power supply.
8. Transducer resonances of at least 2000 Hz.

The transducer should be fully tested and evaluated in the laboratory and on actual Marshall hammer equipment to ensure its proper performance.

Task B--Calibration procedure development. A calibration procedure should be developed for Marshall Hammer equipment installations utilizing the transducer developed in Task A. The procedure is intended to provide a reference standard between different hammer installations to account for the inherent equipment differences at different laboratories. The research necessary to accomplish this is outlined as follows:

1. In order to determine the impact and energy transfer characteristics of the hammer and its support system, it will be necessary to have a standard specimen. Although a standard asphalt concrete mixture could be used for this purpose, there would be certain inherent variability associated with the preparation, mixing, and placement of the asphalt concrete. As an alternative, it would be desirable to have a material other than asphalt concrete that is homogeneous and easily reproduced. The specimen material should be easy to place in a mold and have impact load and compaction characteristics similar to asphalt. The test specimen should require a minimum of processing and technician interaction.

2. Using the specimen standard and the load transducer, an evaluation procedure should be developed to determine process differences between hammers. A recommended approach is to evaluate the overall energy transfer to the test specimen during a typical 70-blow work cycle. This approach will require the incorporation of a data acquisition system and associated software to perform the analysis. The capabilities and limitations of the procedure should be evaluated through a series of benchmark laboratory tests. On the basis of

these tests, modifications to the procedure and rationale should be incorporated as necessary.

Task C--Preliminary field testing. To construct an adequate data base, a series of representative Marshall hammers should be evaluated by the procedure developed in Task B. The data collected should be analyzed to extract trends and to determine if differences in the hammer process can be evaluated with the proposed procedure. Possibly, through interpretation of the data, a single index number may be applied to each hammer to adjust for differences between hammer facilities.

CONCLUSIONS AND RECOMMENDATIONS

Large variations in Marshall hammer test results which occur when a given asphaltic mix is compacted with different compaction hammers are of concern to both public highway agencies and private industry. Although ASTM and AASHTO procedures for testing Marshall properties were originally written for a hand-held, unsupported hammer, currently, the AASHTO standard (T-245) permits the use of a mechanical hammer. This research found that several different makes of mechanical hammer are currently in use, and some agencies use homemade hammers. A wide variation in hammer characteristics was found.

Several hammer-related variables that play a key role in influencing Marshall test results were identified. Of the those surveyed, the base support was most frequently cited as the equipment characteristic that most significantly affects compaction. This finding was verified by the preliminary test results developed in the laboratory study. However, it also was found that discrepancies in test results could be compounded by subtle differences in the interpretation of the procedures and by the use of nonstandard or defective breaking heads. Operator-related factors, factors associated with the compaction device and the breaking head, and their interactions together constitute a fairly complex environment.

Technology (procedure or equipment) for quantifying the effect of key equipment-related variables on Marshall test results is currently not available. In the absence of such technology, several agencies, both in the

United States and in Canada, regularly cooperate in round-robin or mix-exchange programs, which enables them to evaluate their own performance relative to the performance of other participating agencies. An empirical procedure for calibrating a mechanical hammer is currently available. However, this procedure, in which the diameter of a compacted penny is measured, is neither practical nor does it address variations in Marshall properties (stability and flow) resulting from different breaking heads.

It appears that the technology exists to measure the amount of energy delivered to the specimen during the compaction process. However, further development is needed to adapt this technology to the field calibration of Marshall hammers. The development and implementation of a field compaction procedure would provide

1. A means for evaluating the characteristics of different compaction devices and the interaction of these devices with the pedestal and base support (The latter point is important because the pedestal type and base support generally vary from site to site.)

2. A means to identify within- and between-operator variability associated with variations in test procedure

3. A datum that could be used to standardize the compaction process and provide a reference in cases requiring litigation

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Standard Test Method for RESISTANCE TO PLASTIC FLOW OF BITUMINOUS MIXTURES USING MARSHALL APPARATUS[1]

This standard is issued under the fixed designation D 1559; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This method covers the measurement of the resistance to plastic flow of cylindrical specimens of bituminous paving mixture loaded on the lateral surface by means of the Marshall apparatus. This method is for use with mixtures containing asphalt cement, asphalt cut-back or tar, and aggregate up to 1-in. (25.4-mm) maximum size.

2. Significance and Use

2.1 This method is used in the laboratory mix design of bituminous mixtures. Specimens are prepared in accordance with the method and tested for maximum load and flow. Density and voids properties may also be determined on specimens prepared in accordance with the method. The testing section of this method can also be used to obtain maximum load and flow for bituminous paving specimens cored from pavements or prepared by other methods. These results may differ from values obtained on specimens prepared by this method.

3. Apparatus

3.1 *Specimen Mold Assembly*—Mold cylinders 4 in. (101.6 mm) in diameter by 3 in. (76.2 mm) in height, base plates, and extension collars shall conform to the details shown in Fig. 1. Three mold cylinders are recommended.

3.2 *Specimen Extractor*, steel, in the form of a disk with a diameter not less than 3.95 in. (100 mm) and ½ in. (13 mm) thick for extracting the compacted specimen from the specimen mold with the use of the mold collar. A suitable bar is required to transfer the load from the ring dynamometer adapter to the extension collar while extracting the specimen.

3.3 *Compaction Hammer*—The compaction hammer (Fig. 2) shall have a flat, circular tamping face and a 10-lb (4536-g) sliding weight with a free fall of 18 in.(457.2 mm). Two compaction hammers are recommended.

NOTE 1—The compaction hammer may be equipped with a finger safety guard as shown in Fig. 2.

3.4 *Compaction Pedestal*—The compaction pedestal shall consist of an 8 by 8 by 18-in. (203.2 by 203.2 by 457.2-mm) wooden post capped with a 12 by 12 by 1-in. (304.8 by 304.8 by 25.4-mm) steel plate. The wooden post shall be oak, pine, or other wood having an average dry weight of 42 to 48 lb/ft^3 (0.67 to 0.77 g/cm^3). The wooden post shall be secured by four angle brackets to a solid concrete slab. The steel cap shall be firmly fastened to the post. The pedestal assembly shall be installed so that the post is plumb and the cap is level.

3.5 *Specimen Mold Holder*, mounted on the compaction pedestal so as to center the compaction mold over the center of the post. It shall hold the compaction mold, collar, and base plate securely in position during compaction of the specimen.

3.6 *Breaking Head*—The breaking head (Fig. 3) shall consist of upper and lower cylindrical segments or test heads having an inside radius of curvature of 2 in. (50.8 mm) accurately machined. The lower segment shall be mounted on a base having two perpendicular guide rods or posts extending upward. Guide sleeves in the upper segment shall be in such a position as to direct the two segments together without appreciable binding or loose motion on the guide rods.

3.7 *Loading Jack*—The loading jack (Fig. 4) shall consist of a screw jack mounted in a testing frame and shall produce a uniform vertical movement of 2 in. (50.8 mm)/min. An electric motor may be attached to the jacking mechanism.

NOTE 2—Instead of the loading jack, a mechanical or hydraulic testing machine may be used provided the rate of movement can be maintained at 2 in. (50.8 mm)/min while the load is applied.

3.8 *Ring Dynamometer Assembly*—One ring dynamometer (Fig. 4) of 5000-lb (2267-kg) capacity and sensitivity of 10 lb (4.536 kg) up to 1000 lb (453.6 kg) and 25 lb (11.340 kg) between 1000 and 5000 lb (453.6 and 2267 kg) shall be equipped with a micrometer dial. The micrometer dial shall be graduated in 0.0001 in. (0.0025 mm). Upper and lower ring dynamometer attachments are required for fastening the ring dynamometer to the testing frame and transmitting the load to the breaking head.

NOTE 3—Instead of the ring dynamometer assembly, any suitable load-measuring device may be used provided the capacity and sensitivity meet the above requirements.

3.9 *Flowmeter*—The flowmeter shall consist of a guide sleeve and a gage. The activating pin of the gage shall slide inside the guide sleeve with a slight amount of frictional resistance. The guide sleeve shall slide freely over the guide rod of the breaking head. The flowmeter gage shall be adjusted to zero when placed in position on the breaking head when each individual test specimen is inserted between the breaking head segments. Graduations of the flowmeter gage shall be in 0.01-in. (0.25-mm) divisions.

NOTE 4—Instead of the flowmeter, a micrometer dial or stress-strain recorder graduated in 0.001 in. (0.025 mm) may be used to measure flow.

3.10 *Ovens or Hot Plates*—Ovens or hot plates shall be provided for heating aggregates, bituminous material, specimen molds, compaction hammers, and other equipment to the required mixing and molding temperatures. It is recommended that the heating units be thermostatically controlled so as to maintain the required temperature within 5°F (2.8°C). Sui able shields, baffle plates or sand baths shall l used on the surfaces of the hot plates to mi mize localized overheating.

3.11 *Mixing Apparatus*—Mechanical mixi is recommended. Any type of mechanical mix may be used provided it can be maintained the required mixing temperature and will pr vide a well-coated, homogeneous mixture the required amount in the allowable time, a further provided that essentially all of the bat can be recovered. A metal pan or bowl sufficient capacity and hand mixing may al be used.

3.12 *Water Bath*—The water bath shall l at least 6 in. (152.4 mm) deep and shall l thermostatically controlled so as to maintai the bath at 140 ± 1.8°F (60 ± 1.0°C) or 1 ± 1.8°F (37.8 ± 1°C. The tank shall have perforated false bottom or be equipped with shelf for supporting specimens 2 in. (50.8 mn above the bottom of the bath.

3.13 *Air Bath*—The air bath for asphalt cu back mixtures shall be thermostatically co trolled and shall maintain the air temperatu at 77°F ± 1.8°F (25 ± 1.0°C).

3.14 *Miscellaneous Equipment:*

3.14.1 *Containers* for heating aggregate flat-bottom metal pans or other suitable co tainers.

3.14.2 *Containers* for heating bitumino material, either gill-type tins, beakers, pourin pots, or saucepans may be used.

3.14.3 *Mixing Tool*, either a steel trowel (ga den type) or spatula, for spading and han mixing.

3.14.4 *Thermometers* for determining ten peratures of aggregates, bitumen, and bitum nous mixtures. Armored-glass or dial-type the mometers with metal stems are recommende A range from 50 to 400°F (9.9 to 204°C), wit sensitivity of 5°F (2.8°C) is required.

3.14.5 *Thermometers* for water and air bath with a range from 68 to 158°F (20 to 70°C sensitive to 0.4°F (0.2°C).

3.14.6 *Balance*, 2-kg capacity, sensitive to 0. g, for weighing molded specimens.

3.14.7 *Balance*, 5-kg capacity, sensitive to 1. g, for batching mixtures.

3.14.8 *Gloves* for handling hot equipment.

3.14.9 *Rubber Gloves* for removing speci mens from water bath.

3.14.10 *Marking Crayons* for identifyin specimens.

[1] This method is under the jurisdiction of ASTM Committee D-4 on Road and Paving Materials and is the direct responsibility of Subcommittee D04.20 on Mechanical Tests of Bituminous Mixes.

Current edition approved April 30, 1982. Published August 1982. Originally published as D 1559 – 58. Last previous edition D 1559 – 76.

3.14.11 *Scoop*, flat bottom, for batching aggregates.

3.14.12 *Spoon*, large, for placing the mixture in the specimen molds.

4. Test Specimens

4.1 *Number of Specimens*—Prepare at least three specimens for each combination of aggregates and bitumen content.

4.2 *Preparation of Aggregates*—Dry aggregates to constant weight at 221 to 230°F (105 to 110°C) and separate the aggregates to dry-sieving into the desired size fractions.[2] The following size fractions are recommended:

1 to ¾ in. (25.0 to 19.0 mm)
¾ to ⅜ in. (19.0 to 9.5 mm)
⅜ in. to No. 4 (9.5 mm to 4.75 mm)
No. 4 to No. 8 (4.75 mm to 2.36 mm)
Passing No. 8 (2.36 mm)

4.3 *Determination of Mixing and Compacting Temperatures:*

4.3.1 The temperatures to which the asphalt cement and asphalt cut-back must be heated to produce a viscosity of 170 ± 20 cSt shall be the mixing temperature.

4.3.2 The temperature to which asphalt cement must be heated to produce a viscosity of 280 ± 30 cSt shall be the compacting temperature.

4.3.3 From a composition chart for the asphalt cut-back used, determine from its viscosity at 140°F (60°C) the percentage of solvent by weight. Also determine from the chart the viscosity at 140°F (60°C) of the asphalt cut-back after it has lost 50 % of its solvent. The temperature determined from the viscosity temperature chart to which the asphalt cut-back must be heated to produce a viscosity of 280 ± 30 cSt after a loss of 50 % of the original solvent content shall be the compacting temperature.

4.3.4 The temperature to which tar must be heated to produce Engler specific viscosities of 25 ± 3 and 40 ± 5 shall be respectively the mixing and compacting temperature.

4.4 *Preparation of Mixtures:*

4.4.1 Weigh into separate pans for each test specimen the amount of each size fraction required to produce a batch that will result in a compacted specimen 2.5 ± 0.05 in. (63.5 ± 1.27 mm) in height (about 1200 g). Place the pans on the hot plate or in the oven and heat to a temperature not exceeding the mixing temperature established in 4.3 by more than approximately 50°F (28°C) for asphalt cement and tar mixes and 25°F (14°C) for cut-back asphalt mixes. Charge the mixing bowl with the heated aggregate and dry mix thoroughly. Form a crater in the dry blended aggregate and weigh the preheated required amount of bituminous material into the mixture. For mixes prepared with cutback asphalt introduce the mixing blade in the mixing bowl and determine the total weight of the mix components plus bowl and blade before proceeding with mixing. Care must be exercised to prevent loss of the mix during mixing and subsequent handling. At this point, the temperature of the aggregate and bituminous material shall be within the limits of the mixing temperature established in 4.3. Mix the aggregate and bituminous material rapidly until thoroughly coated.

4.4.2 Following mixing, cure asphalt cut-back mixtures in a ventilated oven maintained at approximately 20°F (11.1°C) above the compaction temperature. Curing is to be continued in the mixing bowl until the precalculated weight of 50 % solvent loss or more has been obtained. The mix may be stirred in a mixing bowl during curing to accelerate the solvent loss. However, care should be exercised to prevent loss of the mix. Weigh the mix during curing in successive intervals of 15 min initially and less than 10 min intervals as the weight of the mix at 50 % solvent loss is approached.

4.5 *Compaction of Specimens:*

4.5.1 Thoroughly clean the specimen mold assembly and the face of the compaction hammer and heat them either in boiling water or on the hot plate to a temperature between 200 and 300°F (93.3 and 148.9°C). Place a piece of filter paper or paper toweling cut to size in the bottom of the mold before the mixture is introduced. Place the entire batch in the mold, spade the mixture vigorously with a heated spatula or trowel 15 times around the perimeter and 10 times over the interior. Remove the collar and smooth the surface of the mix with a trowel to a slightly rounded shape. Temperatures of the mixtures immediately prior to compaction shall be within the limits of the compacting temperature established in 4.3.

4.5.2 Replace the collar, place the mold assembly on the compaction pedestal in the mold holder, and unless otherwise specified, apply 50 blows with the compaction hammer with a free fall in 18 in. (457.2 mm). During compaction, the operator shall hold the axis of the compaction hammer by hand as nearly perpendicular to the base of the mold assembly as possible. Remove the base plate and collar, and reverse and reassemble the mold. Apply the same number of compaction blows to the face of the reversed specimen. After compaction, remove the base plate and place the sample extractor on that end of the specimen. Place the assembly with the extension collar up in the testing machine, apply pressure to the collar by means of the load transfer bar, and force the specimen into the extension collar. Lift the collar from the specimen. Carefully transfer the specimen to a smooth, flat surface and allow it to stand overnight at room temperature. Weigh, measure, and test the specimen.

NOTE 5—In general, specimens shall be cooled as specified in 4.5.2. When more rapid cooling is desired, table fans may be used. Mixtures that lack sufficient cohesion to result in the required cylindrical shape on removal from the mold immediately after compaction may be cooled in the mold in air until sufficient cohesion has developed to result in the proper cylindrical shape.

5. Procedure

5.1 Bring the specimens prepared with asphalt cement or tar to the specified temperature by immersing in the water bath 30 to 40 min or placing in the oven for 2 h. Maintain the bath or oven temperature at 140 ± 1.8°F (60 ± 1.0°C) for the asphalt cement specimens and 100 ± 1.8°F (37.8 ± 1.0°C) for tar specimens. Bring the specimens prepared with asphalt cut-back to the specified temperature by placing them in the air bath for a minimum of 2 h. Maintain the air bath temperature at 77 ± 1.8°F (25 ± 1.0°C). Thoroughly clean the guide rods and the inside surfaces of the test heads prior to making the test, and lubricate the guide rods so that the upper test head slides freely over them. The testing-head temperature shall be maintained between 70 to 100°F (21.1 to 37.8°C) using a water bath when requir[e] Remove the specimen from the water ba[th] oven, or air bath, and place in the lower s[eg]ment of the breaking head. Place the up[per] segment of the breaking head on the specim[en] and place the complete assembly in position [on] the testing machine. Place the flowmeter, wh[ere] used, in position over one of the guide rods a[nd] adjust the flowmeter to zero while holding t[he] sleeve firmly against the upper segment of t[he] breaking head. Hold the flowmeter slee[ve] firmly against the upper segment of the brea[k]ing head while the test load is being applied.

5.2 Apply the load to the specimen by mea[ns] of the constant rate of movement of the lo[ad] jack or testing-machine head of 2 in. (50 mm)/min until the maximum load is reach[ed] and the load decreases as indicated by the di[al]. Record the maximum load noted on the testi[ng] machine or converted from the maximum m[i]crometer dial reading. Release the flowme[ter] sleeve or note the micrometer dial readi[ng] where used, the instant the maximum lo[ad] begins to decrease. Note and record the in[di]cated flow value or equivalent units in hu[n]dredths of an inch (twenty-five hundredths [of] a millimetre) if a micrometer dial is used [to] measure the flow. The elapsed time for the t[est] from removal of the test specimen from t[he] water bath to the maximum load determinati[on] shall not exceed 30 s.

NOTE 6—For core specimens, correct the lo[ad] when thickness is other than 2½ in. (63.5 mm) [by] using the proper multiplying factor from Table 1.

6. Report

6.1 The report shall include the followi[ng] information:

6.1.1 Type of sample tested (laboratory sa[m]ple or pavement core specimen).

NOTE 6—For core specimens, the height of ea[ch] test specimen in inches (or millimetres) shall be r[e]ported.

6.1.2 Average maximum load in pound[s]-force (or newtons) of at least three specime[ns] corrected when required.

6.1.3 Average flow value, in hundredths [of] an inch, twenty-five hundredths of a millimet[re] of three specimens, and

6.1.4 Test temperature.

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[2] Detailed requirements for these sieves are given in ASTM Specification E 11, for Wire-Cloth Sieves for Testing Purposes see *Annual Book of ASTM Standards*, Vol 14.02.

TABLE 1 Stability Correlation Ratios[A]

Volume of Specimen, cm³	Approximate Thickness of Specimen, in.[B]	mm	Correlation Ratio
200 to 213	1	25.4	5.56
214 to 225	1 1/16	27.0	5.00
226 to 237	1 1/8	28.6	4.55
238 to 250	1 3/16	30.2	4.17
251 to 264	1 1/4	31.8	3.85
265 to 276	1 5/16	33.3	3.57
277 to 289	1 3/8	34.9	3.33
290 to 301	1 7/16	36.5	3.03
302 to 316	1 1/2	38.1	2.78
317 to 328	1 9/16	39.7	2.50
329 to 340	1 5/8	41.3	2.27
341 to 353	1 11/16	42.9	2.08
354 to 367	1 3/4	44.4	1.92
368 to 379	1 13/16	46.0	1.79
380 to 392	1 7/8	47.6	1.67
393 to 405	1 15/16	49.2	1.56
406 to 420	2	50.8	1.47
421 to 431	2 1/16	52.4	1.39
432 to 443	2 1/8	54.0	1.32
444 to 456	2 3/16	55.6	1.25
457 to 470	2 1/4	57.2	1.19
471 to 482	2 5/16	58.7	1.14
483 to 495	2 3/8	60.3	1.09
496 to 508	2 7/16	61.9	1.04
509 to 522	2 1/2	63.5	1.00
523 to 535	2 9/16	64.0	0.96
536 to 546	2 5/8	65.1	0.93
547 to 559	2 11/16	66.7	0.89
560 to 573	2 3/4	68.3	0.86
574 to 585	2 13/16	71.4	0.83
586 to 598	2 7/8	73.0	0.81
599 to 610	2 15/16	74.6	0.78
611 to 625	3	76.2	0.76

[A] The measured stability of a specimen multiplied by the ratio for the thickness of the specimen equals the corrected stability for a 2½-in. (63.5-mm) specimen.

[B] Volume-thickness relationship is based on a specimen diameter of 4 in. (101.6 mm).

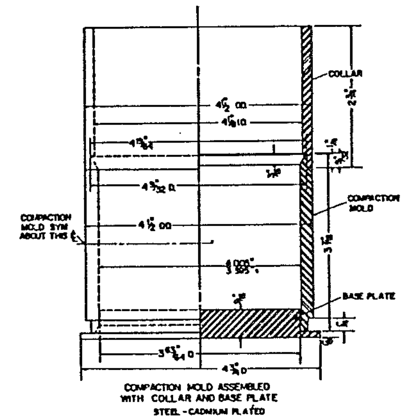


Table of Equivalents for Figs. 1 and 3

Inch-Pound Units, in.	Metric Equivalents, mm	Inch-Pound Units, in.	Metric Equivalents, mm	Inch-Pound Units, in.	Metric Equivalents, mm	Inch-Pound Units, in.	Metric Equivalents, mm
0.005	0.11	11/16	17.5	2 5/16	58.7	4 1/8	104.8
1/32	0.8	3/4	19.0	2 1/2	63.5	4 9/32	108.7
1/16	1.6	7/8	22.2	2 3/4	69.8	4 19/64	109.1
1/8	3.2	15/16	23.8	2 7/8	73.0	4 1/2	114.3
3/16	4.8	1	25.4	3	76.2	4 5/8	117.5
1/4	6.4	1 1/8	28.6	3 1/4	82.6	4 3/4	120.6
9/32	7.1	1 1/4	31.8	3 7/16	87.3	5 1/16	128.6
3/8	9.5	1 3/8	34.9	3 7/8	98.4	5 1/8	130.2
0.496	12.6	1 1/2	38.1	3 63/64	101.2	5 3/4	146.0
0.499	12.67	1 5/8	41.3	3.990	101.35	6	152.4
1/2	12.7	1 3/4	44.4	3.995	101.47	6 1/4	158.8
9/16	14.3	2	50.8	4	101.6	7 5/8	193.7
5/8	15.9	2 1/4	57.2	4.005	101.73	27	685.8

FIG. 1 Compaction Mold

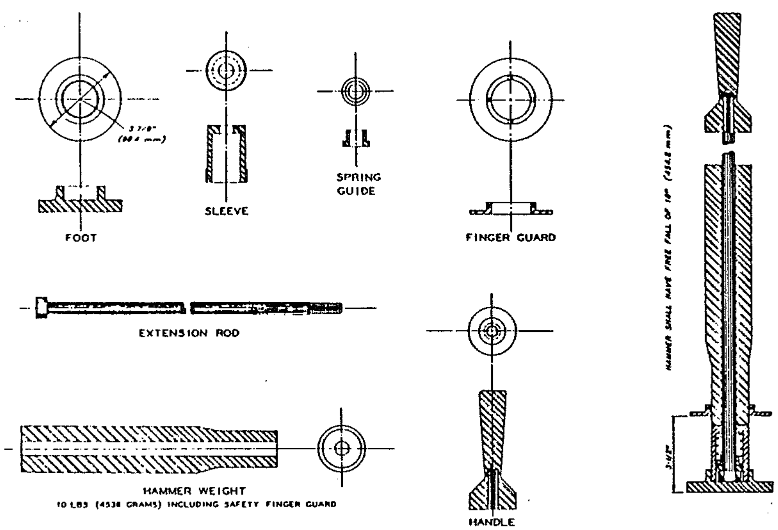
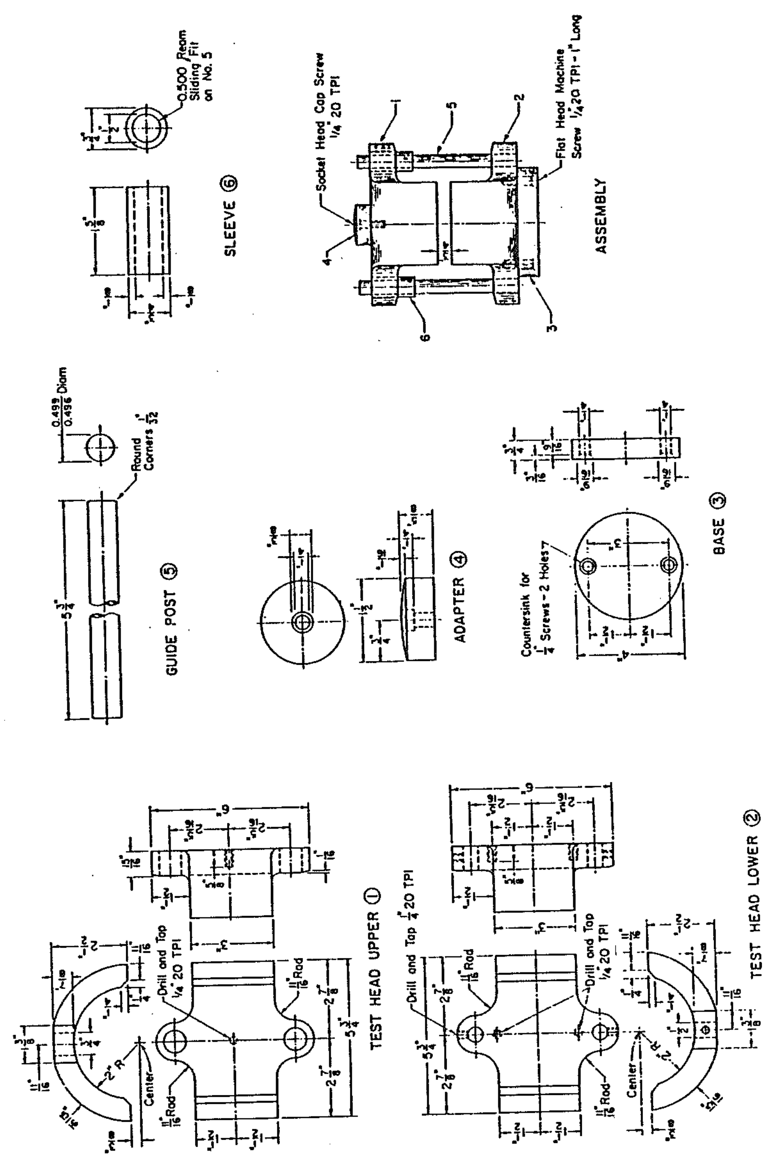


FIG. 2 Compaction Hammer



(Table of Equivalents same as for Fig. 1.)

FIG. 3 Breaking Head

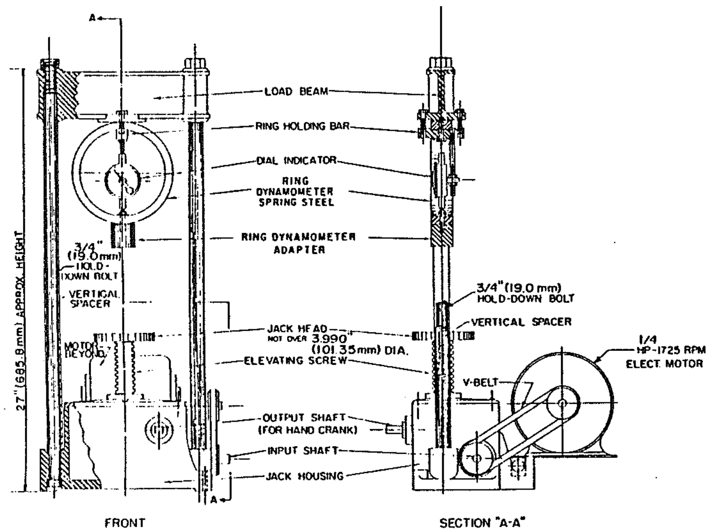


FIG. 4 Compression Testing Machine

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Standard Test Methods for RESISTANCE TO DEFORMATION AND COHESION OF BITUMINOUS MIXTURES BY MEANS OF HVEEM APPARATUS[1]

This standard is issued under the fixed designation D 1560; the number immediately following the designation indicates th year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of las reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 These methods cover the determination of (*1*) the resistance to deformation of compacted bituminous mixtures by measuring the lateral pressure developed when applying a vertical load by means of the Hveem stabilometer, and (*2*) the cohesion of compacted bituminous mixtures by measuring the force required to break or bend the sample as a cantilever beam by means of the Hveem cohesiometer.[2]

2. Applicable Documents

2.1 *ASTM Standard:*

D 1561 Method for Preparation of Bituminous Mixture Test Specimens by Means of California Kneading Compactor[3]

2.2 *California Department of Transportation Method:*

Test 306 Method of Test for Cohesiometer Value[2]

Test 366 Method of Test for Stabilometer Value[2]

3. Significance and Use

3.1 The results of the deformation and cohesion tests can be used for specification purposes or for mix design purposes, or both. For example, these values can be used for specification complicance testing of aggregate properties. They can also be used for specificatio compliance testing of the mix. The cohesior test is sometimes used for fine mixes such a sand mixes wherein cohesion, or tensil strength, is of major or primary importance The cohesion test is also sometimes used fo the design of cold mixes containing emulsifie asphalt.

RESISTANCE TO DEFORMATION

4. Apparatus

4.1 *Stabilometer*—The Hveem stabilomete (Figs. 1 and 2) is a triaxial testing device con sisting essentially of a rubber sleeve within a metal cylinder containing a liquid which reg isters the horizontal pressure developed by a compacted test specimen as a vertical load i applied.

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[1] These methods are under the jurisdiction of ASTM Cor mittee D-4 on Road and Paving Materials and are the dire responsibility of Subcommittee D04.20 on Mechanical Tests Bituminous Mixes.

Current edition approved Nov. 27, 1981. Published Janua 1982. Originally published as D 1560 – 58 T. Last previous ed tion D 1560 – 81.

[2] A more detailed description of the procedures for perforn ing the tests is available on request from the California Dept. Transportation, Transportation Laboratory, 5900 Folsom Blvd Sacramento, Calif. 95819. Also available is a procedure contai ing details regarding the operation and calibration of the stal lometer and the replacement of the stabilometer diaphragm.

[3] *Annual Book of ASTM Standards,* Vol 04.03.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five yea and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for addition standards and should be addressed to ASTM Headquarters. Your comments will receive careful consideration at a meeting of th responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you shoul make your views known to the ASTM Committee on Standards, 1916 Race St., Philadelphia, Pa. 19103.

Standard Method of Test for

Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus

AASHTO DESIGNATION: T 245-82[1]
(ASTM DESIGNATION: D 1559-76)

1. SCOPE

1.1 This method covers the measurement of the resistance to plastic flow of cylindrical specimens of bituminous paving mixture loaded on the lateral surface by means of the Marshall apparatus. This method is for use with mixtures containing asphalt cement, asphalt cut-back or tar, and aggregate up to 1-in. (25.4-mm) maximum size.

2. APPARATUS

2.1 *Specimen Mold Assembly*—Mold cylinders 4 in. (101.6 mm) in diameter by 3 in. (76.2 mm) in height, base plates, and extension collars shall conform to the details shown in Fig. 1. Three mold cylinders are recommended.

2.2 *Specimen Extractor*, steel, in the form of a disk with a diameter not less than 3.95 in. (100 mm) and 1/2 in. (12.7 mm) thick for extracting the compacted specimen from the specimen mold with the use of the mold collar. A suitable bar is required to transfer the load from the ring dynamometer adapter to the extension collar while extracting the specimen.

2.3 *Compaction Hammer*—The compaction hammer (Fig. 2) shall have a flat, circular tamping face and a 10 ± 0.02 lb. (4536 ± 9 g.) sliding weight (including safety finger guard if so equipped) with a free fall of 18 ± 0.06 in. (457.2 ± 1.524 mm.).

NOTE 1—The compaction hammer may be equipped with a finger safety guard as shown in Fig. 2.

NOTE 2—Instead of a hand operated hammer, and associated equipment described in Sections 2.3, 2.4, and 2.5, a mechanically operated hammer may be used provided it has been calibrated to give results comparable with the hand operated hammer.

2.4 *Compaction Pedestal*—The compaction pedestal shall consist of an 8 by 8 by 18-in. (203.2 by 203.2 by 457.2-mm) wooden post capped with a 12 by 12 by 1-in. (304.8 by 304.8 by 25.4-mm) steel plate. The wooden post shall be oak, pine, or other wood having an average dry weight of 42 to 48 lb/ft³ (0.67 to 0.77 g/cm³). The wooden post shall be secured by four angle brackets to a solid concrete slab. The steel cap shall be firmly fastened to the post. The pedestal assembly shall be installed so that the post is plumb and the cap is level.

2.5 *Specimen Mold Holder*, mounted on the compaction pedestal so as to center the compaction mold over the center of the post. It shall hold the compaction mold, collar, and base plate securely in position during compaction of the specimen.

2.6 *Breaking Head*—The breaking head (Fig. 3) shall consist of upper and lower cylindrical segments or test heads having an inside radius of curvature of 2 in. (50.8 mm) accurately machined. The lower segment shall be mounted on a base having two perpendicular guide rods or posts extending upward. Guide sleeves in the upper segment shall be in such a position as to direct the two segments together without appreciable binding or loose motion on the guide rods.

2.7 *Loading Jack*—The loading jack (Fig. 4) shall consist of a screw jack mounted in a testing frame and shall produce a uniform vertical movement of 2 in. (50.8 mm)/min. An electric motor may be attached to the jacking mechanism.

[1] Except for provisions for mechanically operated hammer this method agrees with ASTM D 1559-76

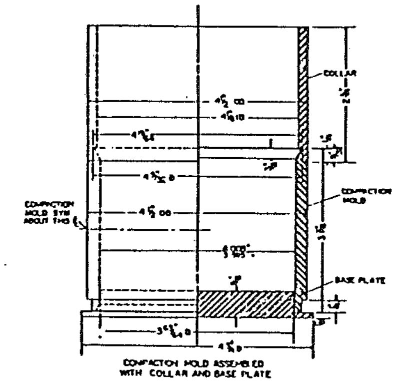


FIG. 1 Compaction Mold.

Table of Equivalents for Figs. 1 and 3

U.S. Customary Units, in.	Metric Equivalents, mm	U.S. Customary Units, in.	Metric Equivalents, mm	U.S. Customary Units, in.	Metric Equivalents, mm	U.S. Customary Units, in.	Metric Equivalents, mm
0.005	0.11	11/16	17.5	2 5/16	58.7	4 1/8	104.8
1/32	0.8	3/4	19.0	2 1/2	63.5	4 9/32	108.7
1/16	1.6	7/8	22.2	2 3/4	69.8	4 19/64	109.1
1/8	3.2	15/16	23.8	2 7/8	73.0	4 1/2	114.3
3/16	4.8	1	25.4	3	76.2	4 5/8	117.5
1/4	6.4	1 1/8	28.6	3 1/4	82.6	4 3/4	120.6
9/32	7.1	1 1/4	31.8	3 7/16	87.3	5 1/16	128.6
3/8	9.5	1 3/8	34.9	3 7/8	98.4	5 1/8	130.2
0.496	12.6	1 1/2	38.1	3 63/64	101.2	5 3/4	146.0
0.499	12.67	1 5/8	41.3	3.990	101.35	6	152.4
1/2	12.7	1 3/4	44.4	3.995	101.47	6 1/4	158.8
9/16	14.3	2	50.8	4	101.6	7 5/8	193.7
5/8	15.9	2 1/4	57.2	4.005	101.73	27	685.8

NOTE 3—Instead of the loading jack, a mechanical or hydraulic testing machine may be used provided the rate of movement can be maintained at 2 in. (50.8 mm)/min while the load is applied.

2.8 *Ring Dynamometer Assembly*—One ring dynamometer (Fig. 4) of 5000 lbf (22.2KN) capacity and sensitivity of 10 lbf (44.5 N) up to 1000 lbf (4.45 KN) and 25 lbf (111.2N) between 1000 and 5000 lbf (4.45 and 22.2 KN) shall be equipped with a micrometer dial. The micrometer dial shall be graduated in 0.0001 in (0.0025 mm). Upper and lower ring dynamometer attachments are required for fastening the ring dynamometer to the testing frame and transmitting the load to the breaking head.

NOTE 4—Instead of the ring dynamometer assembly, any suitable load-measuring device may be used provided the capacity and sensitivity meet the above requirements.

2.9 *Flowmeter*—The flowmeter shall consist of a guide sleeve and a gage. The activating pin of the gage shall slide inside the guide sleeve with a slight amount of frictional resistance. The guide sleeve shall slide freely over the guide rod of the breaking head. The flowmeter gage shall be adjusted to zero when placed in position on the breaking head when each individual test specimen is inserted between the breaking head segments. Graduations of the flowmeter gage shall be in 0.01-in. (0.25-mm) divisions.

NOTE 5—Instead of the flowmeter, a micrometer dial or stress-strain recorder graduated in 0.001 in. (0.025 mm) may be used to measure flow.

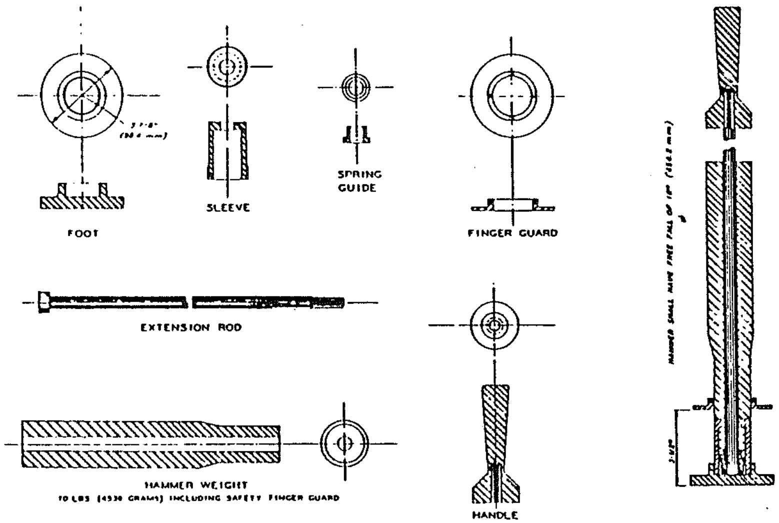


FIG. 2 Compaction Hammer.

2.10 *Ovens or Hot Plates*—Ovens or hot plates shall be provided for heating aggregates, bituminous material, specimen molds, compaction hammers, and other equipment to the required mixing and molding temperatures. It is recommended that the heating units be thermostatically controlled so as to maintain the required temperature within 5 F (2.8 C). Suitable shields, baffle plates or sand baths shall be used on the surfaces of the hot plates to minimize localized overheating.

2.11 *Mixing Apparatus*—Mechanical mixing is recommended. Any type of mechanical mixer may be used provided it can be maintained at the required mixing temperature and will produce a well-coated, homogeneous mixture of the required amount in the allowable time, and further provided that essentially all of the batch can be recovered. A metal pan or bowl of sufficient capacity and hand mixing may also be used.

2.12 *Water Bath*—The water bath shall be at least 6 in. (152.4 mm) deep and shall be thermostatically controlled so as to maintain the bath at 140 ± 1.8 F (60 ± 1 C) or 100 ± 1.8 F (37.8 ± 1 C). The tank shall have a perforated false bottom or be equipped with a shelf for supporting specimens 2 in. (50.8 mm) above the bottom of the bath.

2.13 *Air Bath*—The air bath for asphalt cut-back mixtures shall be thermostatically controlled and shall maintain the air temperature at 77 F ± 1.8 F (25 ± 1 C).

2.14 *Miscellaneous Equipment:*

2.14.1 *Containers* for heating aggregates, flat-bottom metal pans or other suitable containers.

2.14.2 *Containers* for heating bituminous material, either gill-type tins, beakers, pouring pots, or saucepans may be used.

2.14.3 *Mixing Tool*, either a steel trowel (garden type) or spatula, for spading and hand mixing.

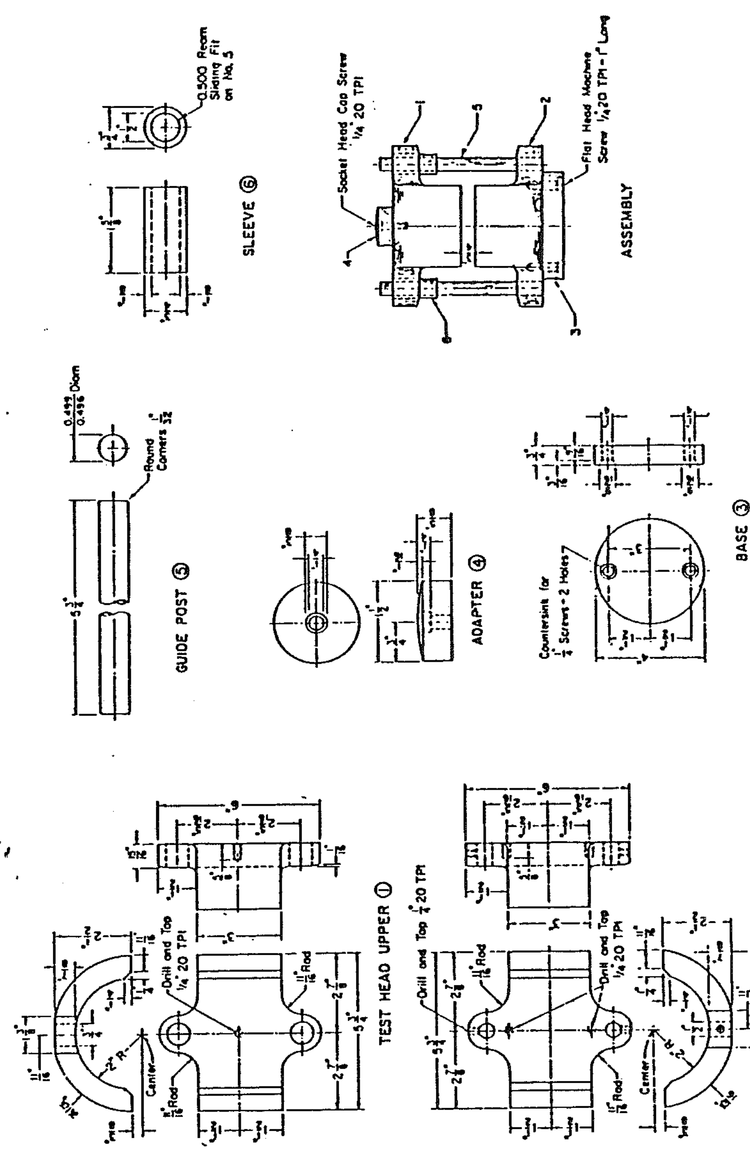
2.14.4 *Thermometers* for determining temperatures of aggregates, bitumen, and bituminous mixtures. Armored-glass or dial-type thermometers with metal stems are recommended. A range from 50 to 400 F (9.9 to 204 C), with sensitivity of 5 F (2.8 C) is required.

2.14.5 *Thermometers* for water and air baths with a range from 68 to 158 F (20 to 70 C) sensitive to 0.4 F (0.2 C).

2.14.6 *Balance*, 2-kg capacity, sensitive to 0.1 g, for weighing molded specimens.

2.14.7 *Balance*, 5-kg capacity, sensitive to 1.0 g, for batching mixtures.

2.14.8 *Gloves* for handling hot equipment.



(Table of Equivalents same as for Fig. 1.)
FIG. 3 Breaking Head.

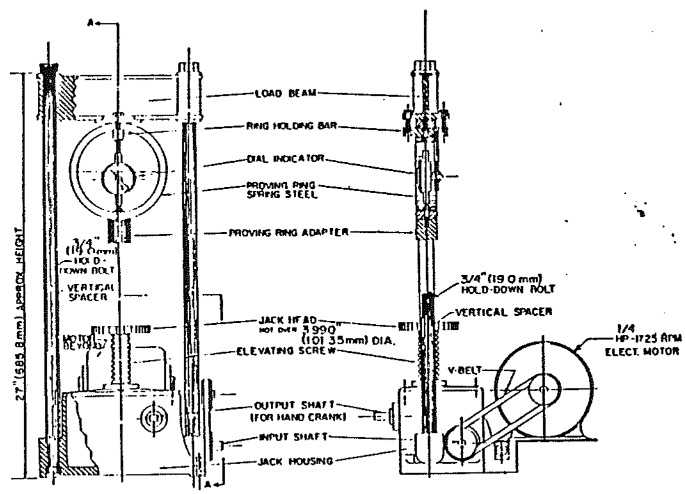


FIG. 4 Compression Testing Machine.

2.14.9 *Rubber Gloves* for removing specimens from water bath.
2.14.10 *Marking Crayons* for identifying specimens.
2.14.11 *Scoop*, flat bottom, for batching aggregates.
2.14.12 *Spoon*, large, for placing the mixture in the specimen molds.

3. TEST SPECIMENS

3.1 *Number of Specimens*—Prepare at least three specimens for each combination of aggregates and bitumen content.

3.2 *Preparation of Aggregates*—Dry aggregates to constant mass at 221 to 230 F (105 to 110 C) and separate the aggregates by dry-sieving into the desired size fractions.[2] The following size fractions are recommended:

1 to 3/4 in. (25.0 to 19.0 mm)
3/4 to 3/8 in. (19.0 to 9.5 mm)
3/8 in. to No. 4 (9.5 mm to 4.75 mm)
No. 4 to No. 8 (4.75 mm to 2.36 mm)
Passing No. 8 (2.36 mm)

3.3 *Determination of Mixing and Compacting Temperatures:*

3.3.1 The temperatures to which the asphalt cement and asphalt cut-back must be heated to produce a viscosity of 170 ± 20 cSt shall be the mixing temperature.

3.3.2 The temperature to which asphalt cement must be heated to produce a viscosity of 280 ± 30 cSt shall be the compacting temperature.

3.3.3 From a composition chart for the asphalt cut-back used, determine from its viscosity at 140 F (60 C) the percentage of solvent by mass. Also determine from the chart the viscosity at 140 F (60 C) of the asphalt cut-back after it has lost 50 percent of its solvent. The temperature determined from the viscosity temperature chart to which the asphalt cut-back must be heated to produce a viscosity of 280 ± 30 cSt after a loss of 50 percent of the original solvent content shall be the compacting temperature.

[2] Detailed requirements for these sieves are given in AASHTO M 92, Wire-cloth Sieves for Testing Purposes.

3.3.4 The temperature to which tar must be heated to produce Engler specific viscosities of 25 ± 3 and 40 ± 5 shall be respectively the mixing and compacting temperature.

3.4 *Preparation of Mixtures:*

3.4.1 Weigh into separate pans for each test specimen the amount of each size fraction required to produce a batch that will result in a compacted specimen 2.5 ± 0.05 in. (63.5 ± 1.27 mm) in height (about 1200 g). Place the pans on the hot plate or in the oven and heat to a temperature not exceeding the mixing temperature established in 3.3 by more than approximately 50 F (28 C) for asphalt cement and tar mixes and 25 F (14 C) for cut-back asphalt mixes. Charge the mixing bowl with the heated aggregate and dry mix thoroughly. Form a crater in the dry blended aggregate and weigh the preheated required amount of bituminous material into the mixture. For mixes prepared with cutback asphalt introduce the mixing blade in the mixing bowl and determine the total mass of the mix components plus bowl and blade before proceeding with mixing. Care must be exercised to prevent loss of the mix during mixing and subsequent handling. At this point, the temperature of the aggregate and bituminous material shall be within the limits of the mixing temperature established in 3.3. Mix the aggregate and bituminous material rapidly until thoroughly coated.

3.4.2 Following mixing, cure asphalt cutback mixtures in a ventilated oven maintained at approximately 20 F (11.1 C) above the compaction temperature. Curing is to be continued in the mixing bowl until the precalculated weight of 50 percent solvent loss or more has been obtained. The mix may be stirred in a mixing bowl during curing to accelerate the solvent loss. However, care should be exercised to prevent loss of the mix. Weigh the mix during curing in successive intervals of 15 min initially and less than 10 min intervals as the weight of the mix at 50 percent solvent loss is approached.

3.5 *Compaction of Specimens:*

3.5.1 Thoroughly clean the specimen mold assembly and the face of the compaction hammer and heat them either in boiling water or on the hot plate to a temperature between 200 and 300 F (93.3 and 148.9 C). Place a piece of filter paper or paper toweling cut to size in the bottom of the mold before the mixture is introduced. Place the entire batch in the mold, spade the mixture vigorously with a heated spatula or trowel 15 times around the perimeter and 10 times over the interior. Remove the collar and smooth the surface of the mix with a trowel to a slightly rounded shape. Temperatures of the mixtures immediately prior to compaction shall be within the limits of the compacting temperature established in 3.3.

3.5.2 Replace the collar, place the mold assembly on the compaction pedestal in the mold holder, and unless otherwise specified, apply 50 blows[3] with the compaction hammer with a free fall in 18 in. (457.2 mm). Hold the axis of the compaction hammer perpendicular to the base of the mold assembly during compaction. Remove the base plate and collar, and reverse and reassemble the mold. Apply the same number of compaction blows to the face of the reversed specimen. After compaction, remove the base plate and place the sample extractor on the end of the specimen. Place the assembly with the extension collar up in the testing machine, apply pressure to the collar by means of the load transfer bar, and force the specimen into the extension collar. Lift the collar from the specimen. Carefully transfer the specimen to a smooth, flat surface and allow it to stand overnight at room temperature. Weigh, measure, and test the specimen.

NOTE 6—In general, specimens shall be cooled as specified in 3.5.2. When more rapid cooling is desired, table fans may be used. Mixtures that lack sufficient cohesion to result in the required cylindrical shape on removal from the mold immediately after compaction may be cooled in the mold in air until sufficient cohesion has developed to result in the proper cylindrical shape.

[3] Apply 75 blows for facilities that will be used by aircraft with tire pressures greater than 100 psi.

4. PROCEDURE

4.1 Bring the specimens prepared with asphalt cement or tar to the specified temperature by immersing in the water bath 30 to 40 min or placing in the oven for 2 h. Maintain the bath or oven temperature at 140 ± 1.8 F (60 ± 1 C) for the asphalt cement specimens and 100 ± 1.8 F (37.8 ± 1 C) for tar specimens. Bring the specimens prepared with asphalt cut-back to the specified temperature by placing them in the air bath for a minimum of 2 h. Maintain the air bath temperature at 77 ± 1.8 F (25 ± 1 C). Thoroughly clean the guide rods and the inside surfaces of the test heads prior to making the test, and lubricate the guide rods so that the upper test head slides freely over them. The testing-head temperature shall be maintained between 70 to 100 F (21.1 to 37.8 C) using a water bath when required. Remove the specimen from the water bath, oven, or air bath, and place in the lower segment of the breaking head. Place the upper segment of the breaking head on the specimen, and place the complete assembly in position on the testing machine. Place the flowmeter, where used, in position over one of the guide rods and adjust the flowmeter to zero while holding the sleeve firmly against the upper segment of the breaking head. Hold the flowmeter sleeve firmly against the upper segment of the breaking head while the test load is being applied.

4.2 Apply the load to the specimen by means of the constant rate of movement of the load-jack or testing-machine head of 2 in. (50.8 mm) min until the maximum load is reached and the load decreases as indicated by the dial. Record the maximum load noted on the testing machine or converted from the maximum micrometer dial reading. Release the flowmeter sleeve or note the micrometer dial reading, where used, the instant the maximum load begins to decrease. Note and record the indicated flow value or equivalent units in hundredths of an inch (twenty-five hundredths of a millimetre) if a micrometer dial is used to measure the flow. The elapsed time for the test from removal of the test specimen from the water bath to the maximum load determination shall not exceed 30 s.

NOTE 7—For core specimens, correct the load when thickness is other than 2½ in. (63.5 mm) by using the proper multiplying factor from Table 1.

TABLE 1 Stability Correlation Ratios[a]

Volume of Specimen, cm[b]	Approximate Thickness of Specimen, in.	mm	Correlation Ratio
200 to 213	1	25.4	5.56
214 to 225	1 1/16	27.0	5.00
226 to 237	1 1/8	28.6	4.55
238 to 250	1 3/16	30.2	4.17
251 to 264	1 1/4	31.8	3.85
265 to 276	1 5/16	33.3	3.57
277 to 289	1 3/8	34.9	3.33
290 to 301	1 7/16	36.5	3.03
302 to 316	1 1/2	38.1	2.78
317 to 328	1 9/16	39.7	2.50
329 to 340	1 5/8	41.3	2.27
341 to 353	1 11/16	42.9	2.08
354 to 367	1 3/4	44.4	1.92
368 to 379	1 13/16	46.0	1.79
380 to 392	1 7/8	47.6	1.67
393 to 405	1 15/16	49.2	1.56
406 to 420	2	50.8	1.47
421 to 431	2 1/16	52.4	1.39
432 to 443	2 1/8	54.0	1.32
444 to 456	2 3/16	55.6	1.25
457 to 470	2 1/4	57.2	1.19
471 to 482	2 5/16	58.7	1.14
483 to 495	2 3/8	60.3	1.09
496 to 508	2 7/16	61.9	1.04
509 to 522	2 1/2	63.5	1.00
523 to 535	2 9/16	65.1	0.96
536 to 546	2 5/8	66.7	0.93
547 to 559	2 11/16	68.3	0.89
560 to 573	2 3/4	69.9	0.86
574 to 585	2 13/16	71.4	0.83
586 to 598	2 7/8	73.0	0.81
599 to 610	2 15/16	74.6	0.78
611 to 625	3	76.2	0.76

[a] The measured stability of a specimen multiplied by the ratio for the thickness of the specimen equals the corrected stability for a 2½-in. (63.5 mm) specimen.

[b] Volume-thickness relationship is based on a specimen diameter of 4 in. (101.6 mm).

5. REPORT

5.1 The report shall include the following information:

5.1.1 Type of sample tested (laboratory sample or pavement core specimen).

NOTE 8—For core specimens, the height of each test specimen in inches (or millimetres) shall be reported.

5.1.2 Average maximum load in pounds-force (or newtons) of at least three specimens, corrected when required,

5.1.3 Average flow value, in hundredths of an inch, twenty-five hundredths of a millimetre, of three specimens, and

5.1.4 Test temperature.

Method 100
UNIT WEIGHT, MARSHALL STABILITY, AND FLOW OF BITUMINOUS MIXTURES

1. SCOPE

1.1 This test method is applicable for evaluation of all hot-mix bituminous pavement mixes in which not more than 10 percent of the aggregate is greater than 1 inch in size.

2. APPARATUS

2.1 **Specimen mold assembly.** Mold cylinders 4 inches in diameter by 3 inches in height, base plates, and extension collars, as shown in figure 100-1, and conforming to details shown in figure 100-2. Six mold cylinders, two base plates, and two extension collars are recommended.

2.2 **Specimen extractor.** A specimen extractor or plunger (figure 100-2) for pushing the compacted specimen from the mold cylinder by the use of a jack and frame.

2.3 **Compaction hammer.** A compaction hammer (figures 100-1 and 100-3) having a flat, circular tamping face and a 10-lb. sliding weight with a free fall of 18 inches. Two compaction hammers are recommended. NOTE: Mechanical hammers may be used when properly correlated with the standard hand hammer by determining number of blows to use to produce same density as that produced by hand hammer.

2.4 **Compaction pedestal.** A pedestal, on which to rest the mold during compaction of the test specimen, consisting of a timber post having a minimum cross section of 5½ by 5½ inch (nominal 6 by 6 inches), capped by a 1-inch-thick steel plate. The pedestal cap may consist of a 12- by 12- by 1-inch steel plate, supported by a 12- by 12- by 2-inch wood section over the 6- by 6-inch post if arrangements are made for placing the compaction mold directly over the 6- by 6-inch post. The compaction pedestal must be placed on a concrete floor slab or base resting on the ground, or directly over an interior building column or similar location. Wooden floors or unsupported areas of concrete floors are unsuitable supports for the compaction pedestal. The provision of a pedestal in accordance with these requirements is very important; otherwise the compaction obtained will not agree with field conditions.

2.5 **Specimen mold holder.** A steel or cast-iron holder (figure 100-2) consisting of a semicircular base and a circular top to hold the specimen mold in place during compaction of the specimen. The top section should be flanged to fit over the collar of the specimen mold and should be attached to the base by means of a fulcrum on one side and a tension spring on the other. Two holes shall be provided in the base for mounting the holder on the compaction pedestal. The specimen mold holder shall be mounted on the pedestal cap so that the center of the mold is over the center of the post.

2.6 **Breaking head.** A breaking head (figures 100-1 and 100-4) consisting of upper and lower cylindrical segments or test heads which have an accurately machined inside radius of curvature of 2 inches. The lower segment shall be mounted on a base having two perpendicular guide rods or posts extending upward. Guide sleeves in the upper segment shall be posi-

APPENDIX B. QUESTIONNAIRE

NAME: TEL:
AGENCY: DATE:

- The Marshall procedure is widely used for the design and control of hot-mix paving mixtures.

- Very often there are discrepancies between test results when samples are compacted and tested in different Marshall equipment

1. Are you aware of or have you experienced these discrepancies?

   Yes No

   Comments:

2. What (make of) Marshall compaction equipment does your department/agency use?

Manufacturer	Model No.
Rainhart	
Soiltest	
Forney	
Pine	

   How old is the equipment?

3. In your opinion, are there significant differences in Marshall compaction equipment made by different manufacturers?

   Yes No

   Comments:

   If "yes", what are some of the differences?

4. Do you think the differences between test results are due to:

   a. ______ equipment-related factors

   b. ______ operator-related factors

   c. ______ both (a) and (b)

5. Based on your experience, which factors related to the compaction equipment are responsible for the discrepancies in test results?

   _____ weight of the hammer

   _____ height of free fall

   _____ friction between rod and hammer

   _____ base type

   _____ mold restraint

   _____ alignment of hammer

   _____ dynamic response from energy transfer during impact

   _____ base support (foundation)

   _____

   _____

   _____

6. In your opinion, what factors associated with the Marshall Stability/Flow equipment affect reproducibility of test results?

7. Do you know of, or can you recommend, any procedure or equipment that could be used to quantify any of the equipment-related variables that affect test results?

8. Do you know or can you recommend any equipment or procedure that could be used to calibrate the Marshall compaction equipment?

Yes No

Comments:

9. Is your Marshall compaction equipment located on

_____ the ground floor

_____ first floor

_____ second floor

10. Is your Marshall compaction equipment mounted on

_____ wood block

_____ concrete floor

_____ bed rock

APPENDIX C.

THE PENNY TEST*

Clean top surface of pedestal, both surfaces of Marshall mold bottom and face of Marshall hammer. Inspect hammer for tightness of joint between sleeve and foot and tighten if necessary. (In come cases it may be preferable to tack weld this joint to maintain tightness).

Assemble Marshall mold bottom, mold and collar, and secure to top of pedestal with mold holder.

Place a copper one cent piece on the mold bottom in approximate center. Do not attempt to maintain center position with mechanical guides or adhesives.

Place Marshall hammer in mold with hammer face resting flat on penny. Hold handle in this position with light downward pressure. Raise and drop sliding weight 5 times. (Do not allow weight to bounce). Remove and inspect penny and replace with slightly different orientation.

Replace penny and repeat above operation until a total of 35 blows has been applied.

Scribe two diameters at right angles to each other on one face of penny. With micrometer measure these two diameters and two other diameters equi-distant between them. Average the four measurements to obtain expanded diameter of penny.

To evaluate pedestal, process nine pennies as above and average results to obtain measure of pedestal reaction.

*Courtesy of Mr. Wade Betenson, Utah DOT